AEDC-TR-79-7

ONLINE MONITORING OF COMPRESSOR BLADE STRESS: AN IMPROVED SYSTEM

Riley B. Fowler
ARO, Inc., a Sverdrup Corporation Company

ENGINE TEST FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

April 1979

Final Report for Period November 1977 — July 1978

Approved for public release; distribution unlimited.

Prepared for

ARNOLD ENGINEERING DEVELOPMENT CENTER/DOTR
ARNOLD AIR FORCE STATION, TENNESSEE 37389

NOTICES

APPROVAL STATEMENT

This report has been reviewed and approved.

Eules L. Hively

EULES L. HIVELY
Project Manager, Research Division
Directorate of Test Engineering

Approved for publication:

FOR THE COMMANDER

Robert W. Crossley

ROBERT W. CROSSLEY, Lt Colonel, USAF
Acting Director of Test Engineering
Deputy for Operations

UNCLASSIFIED

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AEDC-TR-79-7	2. GOVT ACCESSION NO.
	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): ONLINE MONITORING OF COMPRESSOR BLADE STRESS: AN IMPROVED SYSTEM	5. TYPE OF REPORT & PERIOD COVERED: Final Report, Nov 1977 - July 1978
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Riley B. Fowler, ARO, Inc., a Sverdrup Corporation Company	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Arnold Engineering Development Center, Air Force Systems Command, Arnold Air Force Station, Tennessee 37389	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Program Element 65807F
11. CONTROLLING OFFICE NAME AND ADDRESS: Arnold Engineering Development Center/OIS, Air Force Systems Command, Arnlod Air Force Station, Tennessee 37389	12. REPORT DATE: April 1979
	13. NUMBER OF PAGES: 72
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available in DDC.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

compressor blades	optical data
stresses	Fourier analysis
monitors	frequency spectrum
fatigue	computers
predictions	interfaces

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The field of compressor blading design and analysis was researched, and results are presented. The system specifications for an improved online stress-monitoring system are stated on the basis of these results. These specifications are believed to cover present and future test needs. A hardware and software system design is presented which satisfies these specifications.

DD FORM 1473, 1 JAN 73 — EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

20. ABSTRACT (Continued)

A three-level hardware design is proposed to provide for flexibility, modularity, and expansion. Basic ground rules and concepts for software design are also established. Project resource limitations did not allow recording of alternate analysis methods that were considered in choosing the analysis requirements included in this report (e.g., Fourier analysis on all channels, display of data for operator interpretation). For the same reason, alternate hardware and software considerations (microprocessor/channel, large computer online analysis with preprocessing) are omitted. The analysis methods, hardware, and software presented in this report are believed to provide a pertinent, cost-effective solution (considering present research data) to the problem of improving online monitoring systems and their ability to perceive and predict fatigue danger. This improved ability could greatly reduce the risk of destroying a jet engine compressor.

PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC). The results of the research were obtained by ARO, Inc., AEDC Division (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee, under ARO Project Number E32I-P4A. The Air Force project manager was Mr. Eules Hively. The manuscript was submitted for publication on December 14, 1978.

The author extends his appreciation to the following individuals and companies for their advice, provision of reference materials, and general guidance in the areas of online and offline monitoring of stress data, the design of compressor blades, and current vibrational analysis methods: Messrs. R. S. Ballard, D. L. Davidson, J. L. Welch, J. L. Grissom, P. E. McCarty, G. W. Konyndyk, and J. C. Childers, ARO, Inc.; Mr. Dave Hillard, Pratt and Whitney Corporation, West Palm Beach, Florida; Mr. Pete Papadakis, Detroit Diesel Allison, Indianapolis, Indiana; Messrs. Ray Bucy and W. J. Rakowski, General Electric Corporation, Cincinnati, Ohio; Messrs. G. M. Bode and R. R. Smalley, Lewis Research Center, Cleveland, Ohio; Mr. R. M. Stewart, Institute of Sound and Vibration Research, The University of Southampton, England; Spectral Dynamics Corporation, San Diego, California; Signal Processing Systems Corporation, Waltham, Massachusetts; EMR Corporation, Sarasota, Florida; GenRad, Time/Data Division, Santa Clara, California; Plessy Microsystems, Irvine, California.

CONTENTS

ILLUSTRATIONS

TABLES

1.0 INTRODUCTION

Online monitoring of compressor blade stress involves the theory of fatigue stress analysis, which includes the following design tools: finite element, pure pull, moment, and torque load analysis. In addition, precision laboratory experiments and holograms of compressor blading are used to define and determine blade performance characteristics and fatigue stress limits. This combination of theoretical and experimental analysis is used to determine performance margin limits that can be used while the output of dynamic vibrational instrumentation and data display systems is observed. Present online analysis techniques rely almost exclusively on the display of data for observance by trained stress observers who are intimately familiar with the electrical representation and display of fatigue waveforms and performance margin limits, as well as how these limits are affected by various compressor operational conditions.

Preliminary research into the field of stress analysis and the observance of stress data indicated that improvements could be made if the actions performed by the skilled observer could be duplicated by an automated data processor and analyzer. This can be accomplished by placing 1) pertinent design information, 2) specific details concerning a particular engine, and 3) natural human filtering techniques and anticipatory characteristics into a nonvolatile machine memory. This memory would be analogous to the skilled observer's memory and experience. The machine memory could then be manipulated by machine-executable algorithms in a manner similar to the methods used by the human analyzer. This approach provides uniform analysis, split-second response to any impending fatigue danger, and more sophisticated and intelligent display of pre-analyzed data. Section 2.0 of this report provides the research and background information necessary for understanding the skills possessed by present online stress observers.

Section 3.0 states conceptual and specific requirements (present and future) for an improved online monitoring system based upon the improvement philosophy and the research data provided in Section 2.0. Section 4.0 provides a conceptual design which includes hardware and software system concepts and specific methods of system software development. Section 5.0 summarizes overall activities and draws conclusions with respect to future use of this system.

2.0 COMPRESSOR BLADING DESIGN AND ANALYSIS

This field of study is examined because test requirements emanate from the design and analysis of compressor blades. This chapter provides background information only. The sources of specific design and analysis information are referenced.

2.1 FATIGUE STRESS

Stress and fatigue knowledge begins with a basic understanding of Fig. 1, taken from Ref. 1. The stress (σ) in pounds per square inch (psi) is plotted versus time. Tensile stresses are considered positive, compressive stresses negative. The stress at any point on any blade will exhibit the characteristics indicated by Fig. 1. Furthermore, these stress characteristics can take place in four dimensions, as shown in Fig. 2. The resultant stress (σ) at any given time (t_g) would be given by Eq. (1).

$$\left|\sigma_{r_{t_g}}\right| = \sqrt{\sigma^2_{x_{t_g}} + \sigma^2_{y_{t_g}} + \sigma^2_{z_{t_g}}} \qquad (1)$$

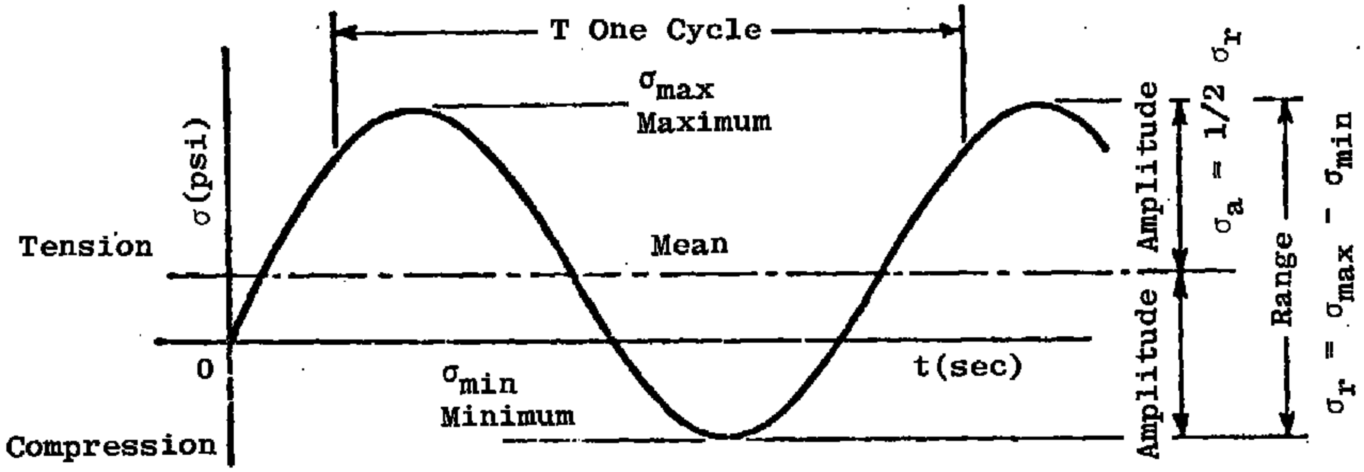
The failure of any one blade is due primarily to fatigue. Fatigue cracks usually start at a point on the surface for two reasons (Ref. 1):

1. Most fatigue failures originate at points which are subjected to tensile stresses, which are maximum at the surface of a member when it is subjected to bending and torsion.

2. Points of stress concentration (stress raisers) often form on the surface due to the process of shaping a member. They may take the form of relatively sharp changes in lateral dimensions of the member such as toolmarks, notches, scratches, nicks, sharp fillets, or inspection stamps. Reference 1 indicates that fatigue failure of an airplane propeller blade was found to have started in the indentation left by a patent number stamp.

Figures 3 and 4 indicate the number of stress cycles (N) at a given peak-to-peak stress value (σ) required for fatigue failure. These figures also indicate that two different materials present two basically different σ-N diagrams. If the σ-N diagram becomes and remains practically horizontal through a very large number of stress cycles (10^8, for example), then the material is said to have a fatigue limit. The maximum stress given in Figs. 3 and 4 is determined for a stated mean stress and stress ratio (Fig. 1). Therefore, all three stress conditions must be known.

It has also been determined that for any given material, the size of the specimen subjected to fatigue is important (Ref. 1). Smaller parts will exhibit a higher fatigue limit than larger parts of identical material and shape under the same stress conditions. Since the fatigue limit of metals depends upon so many independent factors, no reliable tables of general relationships between the fatigue limits and ultimate strength can be compiled at present (Ref. 1).



Mean Stress $\left(\sigma_m = 1/2\ (\sigma_{max} + \sigma_{min})\right)$

Stress Ratio $\left(R = \dfrac{\sigma_{min}}{\sigma_{max}}\right)$

(From Ref. 1)

Figure 1. Basic stress versus time graph for a specimen subjected to fatigue.

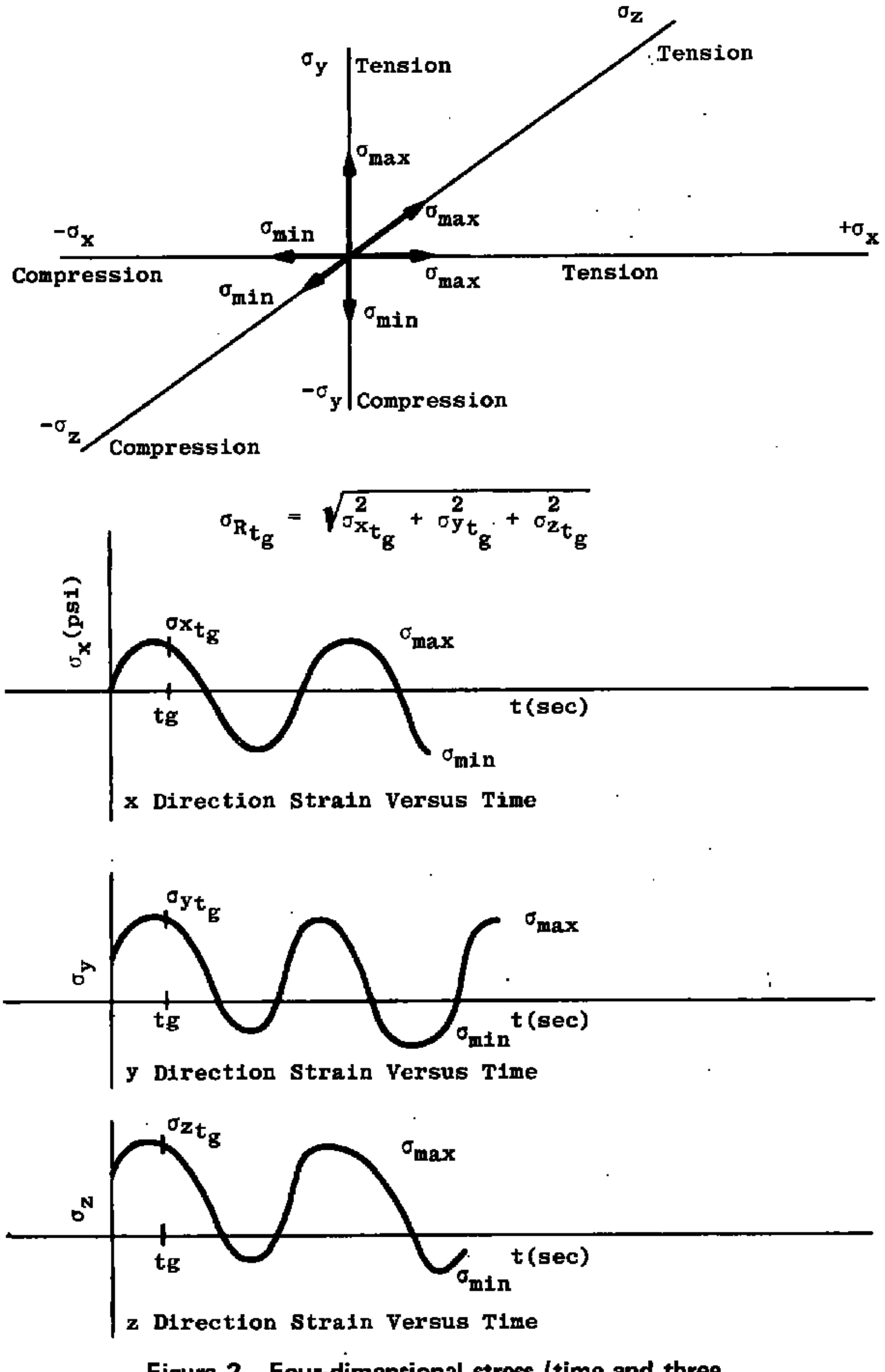


Figure 2. Four-dimensional stress (time and three physical directions).

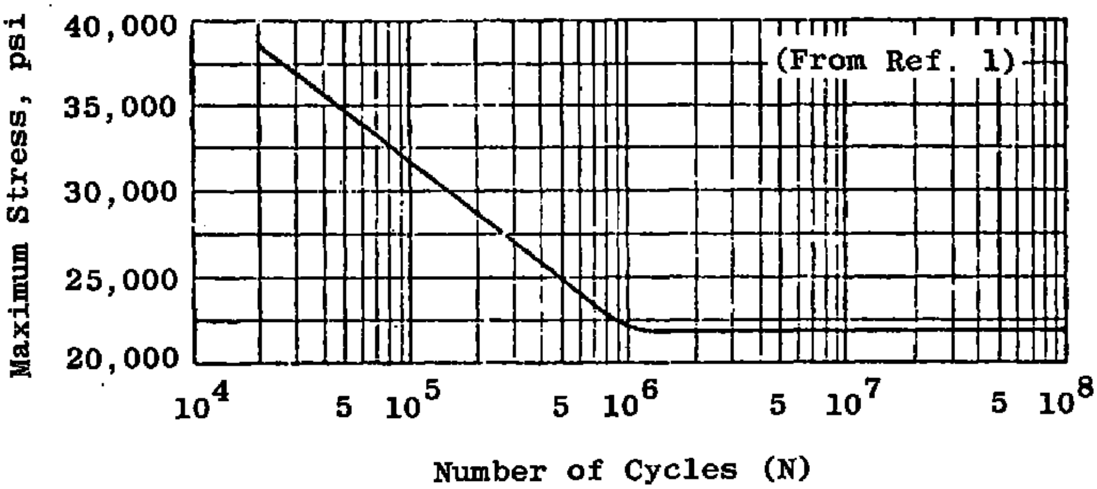


Figure 3. σ-N diagram for steel specimen.

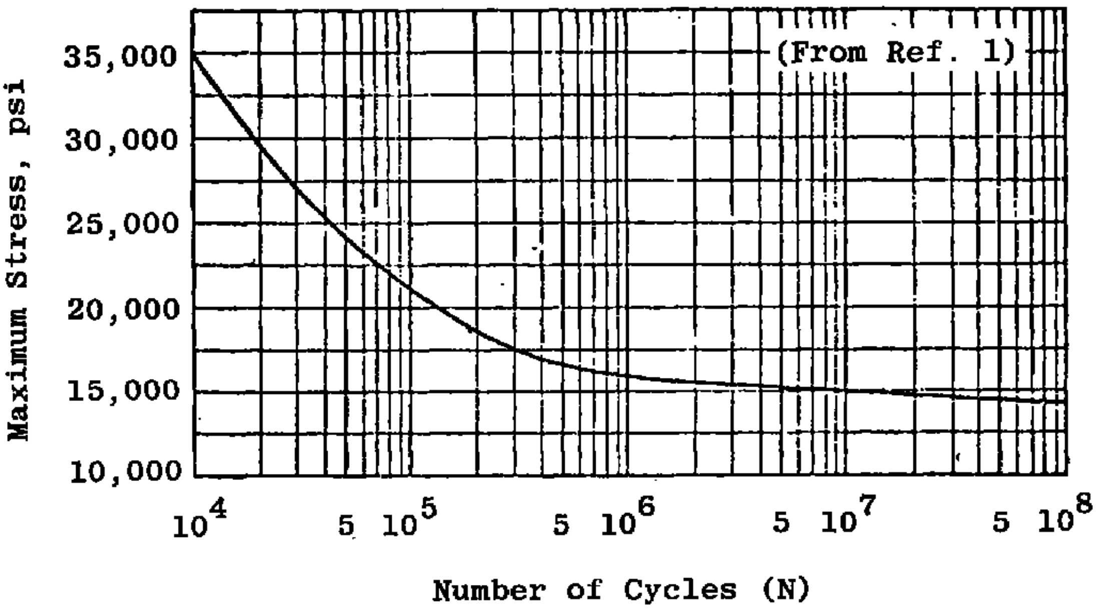


Figure 4. σ-N diagram for aluminum alloy specimen.

Because the relationship between alternating stress amplitude and mean stress determines fatigue limit, one must consider these factors in design. One of the simplest methods for doing this is Soderberg's method (Figs. 5 and 6). The x-axis represents mean stress for a given material, and the y-axis represents the alternating stress values. When the alternating stress is zero, the maximum allowable mean stress will be the yield point ($a = \sigma_{yp}$). Conversely, when the mean stress is zero, the maximum amplitude for alternating stress will be the fatigue limit ($b = \sigma_{FL}$). These two points represent boundary conditions. Some curve connecting them would represent their actual relationship. Experimental data indicate that a straight line drawn between the two points can be used. Design procedure consists of locating the mean value of stress (σ_a) for a given specimen on the x-axis and drawing a semicircle around σ_a. Few specimens have yet been found to fail if the points determined by the coordinates σ_m and σ_a lie within the triangle ab0. Fig. 6 indicates the same analysis with safety factors applied.

A practical design example is given in Ref. 2 where the steady-state stresses are calculated by using the Henky-von Mises equation. The steady-state stress is then plotted on the appropriate Goodman diagram, which is very similar to the Soderberg diagram. From this plot, the allowable amplitude of alternating stress is determined.

2.2 VIBRATIONAL MODES PRODUCING FATIGUE STRESS

We will now examine the different vibration modes which can exist in axial-flow compressor blades. Fig. 7, taken from Ref. 3, indicates different vibrational modes. Flexural (i.e., bending), torsional, and edgewise vibrations can occur. It is important to remember that steady-state centrifugal forces and steady-state air loading on rotor blades produce the mean stress values for any given blade. The alternating stress values are produced by fixed wake excitation, flutter (aeroelastic instability), rotating stall cell excitation, buffeting effects due to random disturbances in the airflow, rub or impact, and engine vibrations fed into the blades due to nonconcentric shafts, imperfect bearings, or rotor imbalance.

The characteristics of compressor blade vibration for some of these vibrational modes are described in Table 1, which is taken from Ref. 4. (Further discussion of these characteristics may be found in Ref. 5.) Figure 8 indicates typical waveforms produced by strain gages for various types of vibrational modes. Figure 9 further illustrates a typical engine-ordered waveform and frequency spectrum just before blade flutter occurs. Figure 10 illustrates the same blade under flutter conditions. In none of these cases are the waveforms pure sinusoids. It is apparent that the pure sinusoidal waveform (indicated in Fig. 1) becomes, in actual testing, a harmonic waveform. Stress analysts are most familiar with this pure sinusoidal waveform and the definitions associated with it.

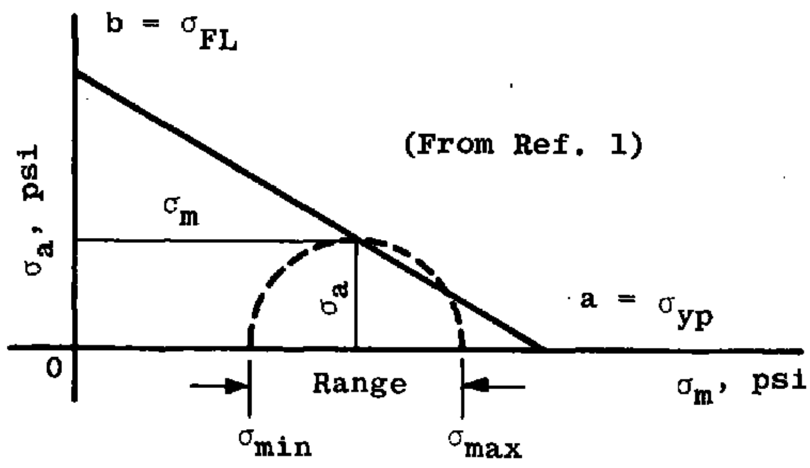


Figure 5. Soderberg triangle.

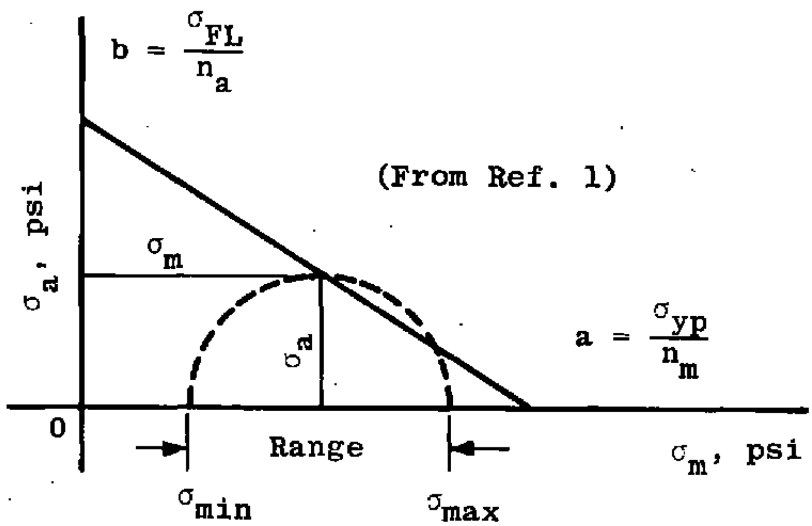
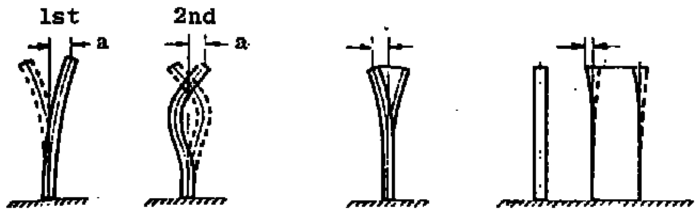


Figure 6. Soderberg triangle with factors of safety n_a and n_m applied.

Flexural Modes | **Torsional** | **Edgewise**



For All Flexural Modes of Cantilever

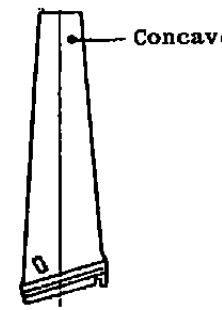
Maximum Root Section Stress $= \sigma_{max} = 2\pi \frac{y}{k}\sqrt{E\rho}\ af$

- k - Radius of Gyration Root Section
- y - Distance from Neutral Axis to Point of Maximum Stress
- E - Young's Modulus
- ρ - Density
- a - Total Amplitude
- f - Frequency

Typical Fatigue Rig Failing Amplitudes 10^7 Cycles

	af
Aluminium	±5.5 ft/sec
Steel	±6.5 ft/sec
Titanium	±11.0 ft/sec
Glass Fibre Laminate	±12.0 ft/sec

Typical Strain Gage Position and Calibration



Mode	Frequency, cps	mv RMS for ±1 ft/sec
1F	250	1.2
2F	952	1.1
1T	1,574	0.85
1E	1,936	0.68

(From Ref. 3)

Figure 7. Specification of vibration.

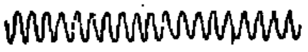
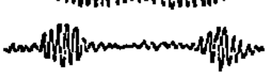
Table 1. Characteristics of Compressor Blade Vibration (Ref. 14)

Characteristics	Cause of Vibration			
	Static Nonuniform Flow	Stall Flutter	Rotating Stall Cells	
			Steady	Unsteady
Stage of Blading	Any (Early and Late)	First (L.P. Only)	Early	Early
Speed of Occurrence	Any	60 to 80-percent N	<70 to 80-percent N	<70 to 80-percent N
Amplitude Variation with Speed	Isolated Peak	Isolated Peak	Isolated Peak	Many Peaks
Amplitude Variation with Time	Steady	Steady	Steady	Fluctuating
Mode of Vibration	Any	1F or 1T	Lower Modes	Lower Modes
Frequency Relationship to Compressor Speed	Fixed E.O. Integer	Not Tied	Fixed E.O. Noninteger	Fixed E.O. Noninteger
Phase Change through Blade Response	180 deg	No Change	180 deg	Irregular
Amplitudes of Different Blades with Speed	Separated Peaks	Together	Separated	Close Together
Overall Comparison of Peak Amplitudes	2:1	>4:1	2:1	2:1
Phase Relation between Different Blades	Changes up to 180 deg and Back	None	Changes up to 180 deg and Back	Indeterminant

Engine-Ordered (E.O.)

First Flexural (1F)

First Torsional (1T)

Example of Waveform	Im*	Symbol Code	Type of Vibration**	Comments
	Usually 0-10	R	R	Nearly constant amplitude with vib. freq. being an <u>integral</u> multiple of rotational speed.
	10-35	SM	SFV	"Slight Modulation": Small magnitude of flow separation or turbulence present.
	35-65	M	SFV	"Moderate Modulation": Moderate turbulent excitation.
	65-80	HM	SFV	"Heavy Modulation": Strong turbulent excitation (cascade flow separation, or possibly much free-stream turbulence).
	80-100	VM	SFV	"Violent Modulation": Same as for "HM," but stronger.
	Variable	P	---	Pulsing-type response occurring intermittently, indicative of time-varying turbulence level, or other excitation source.
	---	---	Beating	Regular maxima and minima of vibratory stress with phase change of waveform frequency at each minimum: Do <u>not</u> count cycles through a minimum. (See Den Hartog, Ref. 5.)
	---	---	Rub or Impact	Kick in stress on every rub encounter (usually 1/rev) on passage of impact excitation (can be caused on rotor blades by an off-angle stator).
	---	RS	Rotating Stall	Typical rotating stall pattern, each kick denoting leading edge of stall cell, with SFV within the stall cell, then clearing until the stall cell comes by again.
	---	RS	Rotating Stall	Rotating stall pattern frequently seen on rotor blades, separated flow vibration, excited by the stall, not clearing up between stall cells.
	---	RS	Rotating Stall	Rotating stall pattern when stall cells cover only small circumferential extent or for heavily damped structural response (pivoted stators, for example).
 (Rotor Blades)  (Stator Vanes)			Stall Pulse Surge	Vibratory stress blossoms rapidly during initial portion of pulse, and stress may "burst" more than once during the pulse (2 are shown here). Blade response is in one (or more) of its natural modes. Pulse (surge) is self-clearing in nature, but may recur at frequent intervals until stall-clearing action has become effective.
	Usually 0-30	*** L.C.	Instability	Aero-elastic instability, usually occurring in first flex or first torsion mode of the blading. Looks like resonance except its frequency is not necessarily integral-order, and is usually encountered while increasing stage loading.

$$*\mathrm{Im} = \frac{(\text{max stress}) - (\text{min stress})}{(\text{max stress})} = \frac{\sigma_R}{\sigma_{max}}$$

**R = Resonance; sfv = separated flow vibration.

***LC = Limit cycle instability, a long-used term implying the characteristics of aeroelastic instability encountered at high cascade loading conditions.

(a) Duration of stall pulse depends on the air-induction system volumetric dynamics (small volumes yield short pulse duration).

Figure 8. Terminology and typical waveform characteristics for stress signal interpretation.

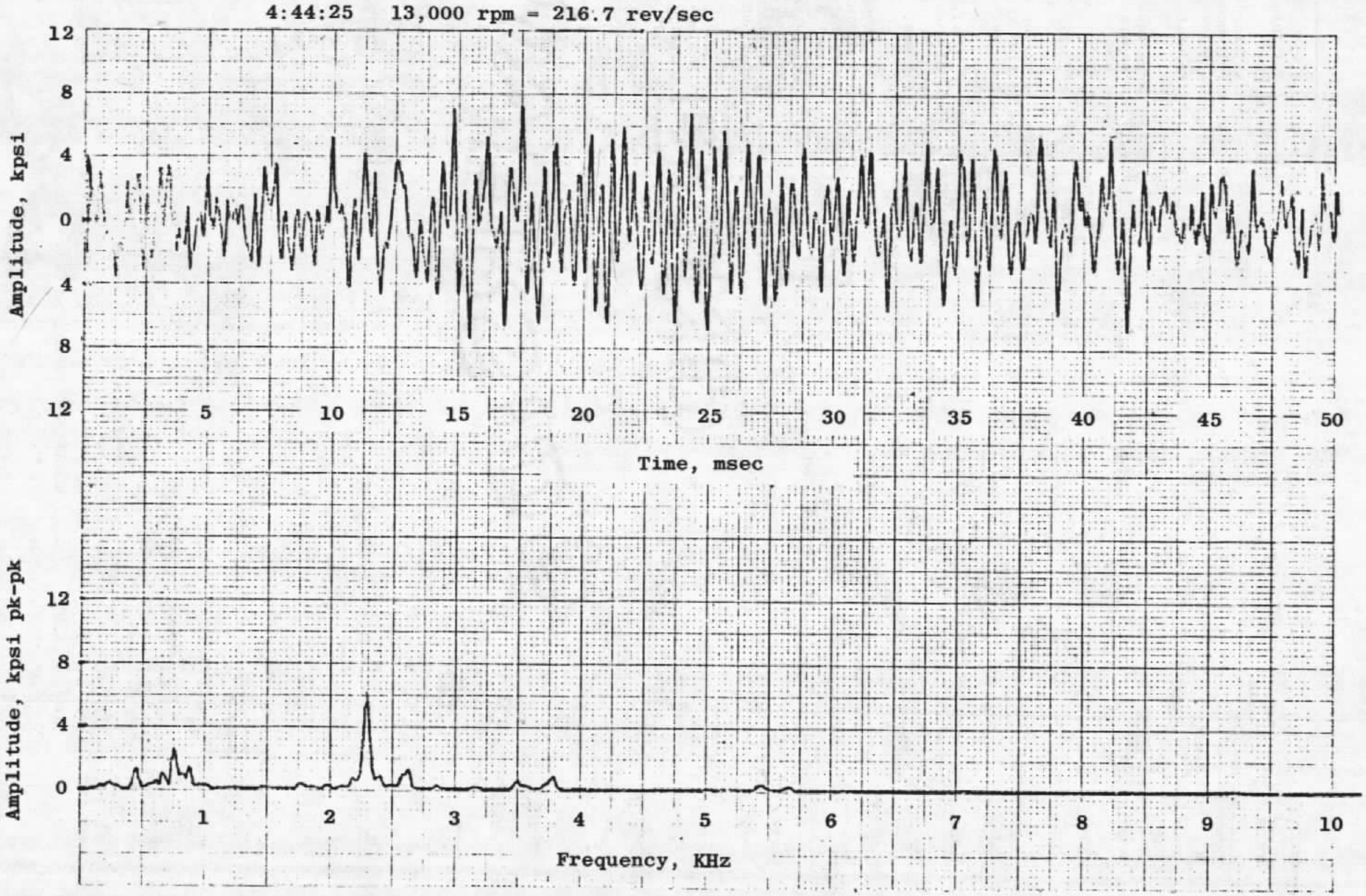


Figure 9. Time and frequency domain representation of rotor-ordered waveform just prior to flutter for an axial-flow compressor.

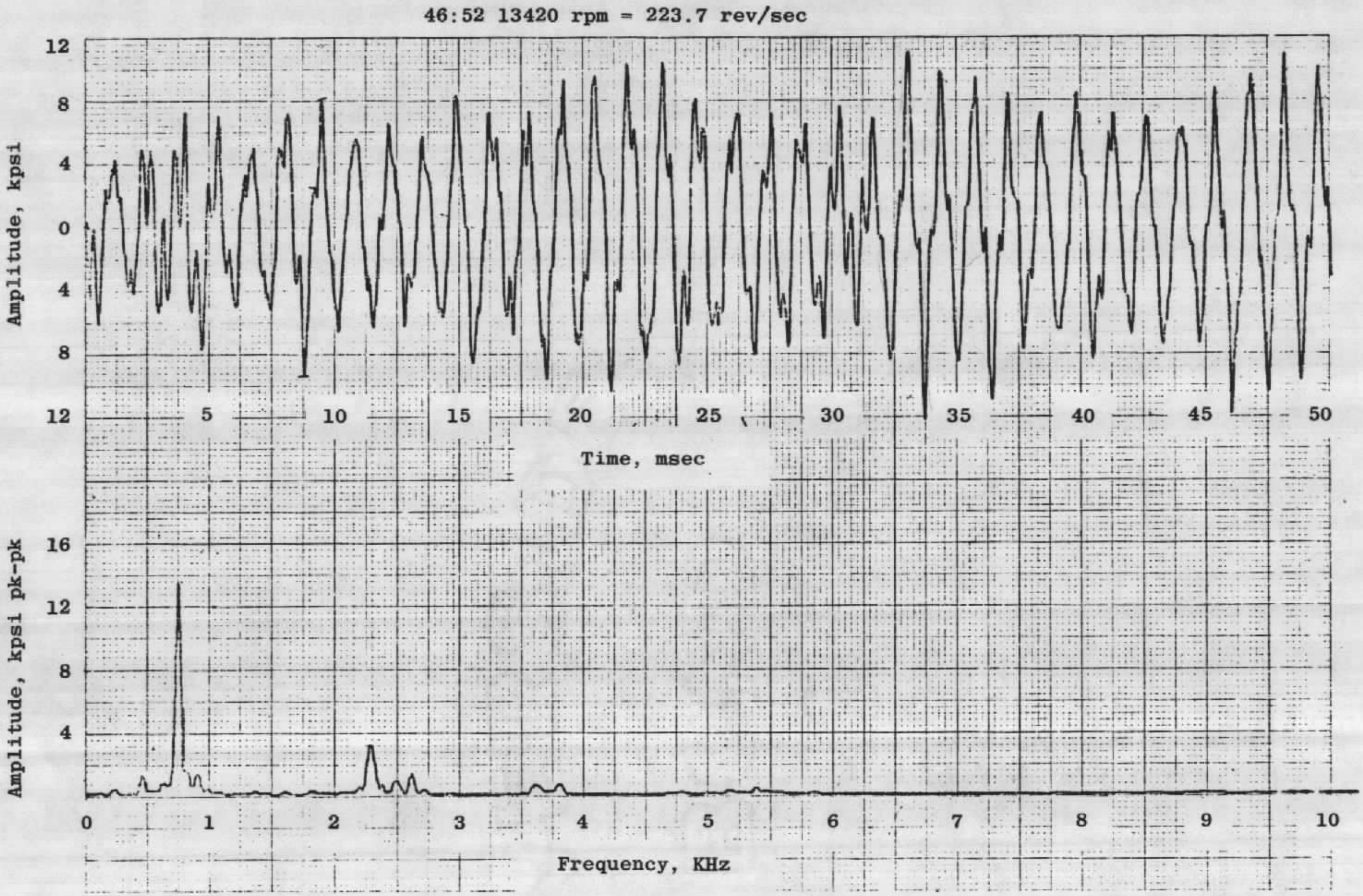


Figure 10. Time and frequency domain representation of a flutter waveform for an axial-flow compressor.

Therefore, designers and stress analysts need to observe the frequency content of the waveforms (frequency domain) as well as overall stress amplitudes and waveform shapes (time domain).

2.3 FREQUENCY DOMAIN ANALYSIS OF FATIGUE WAVEFORMS

Frequency domain information is obtained by dividing the overall waveform into an infinite series of pure sine and cosine functions. This is called the Fourier series and is given in Eqs. (2) through (6), taken from Ref. 6.

$$f(t) = a_o + a_1 \cos \omega_o t + a_2 \cos 2\omega_o t + \ldots\ldots a_n \cos n\,\omega_o t$$
$$+ b_1 \sin \omega_o t + b_2 \sin 2\omega_o t + \ldots\ldots b_n \sin n\,\omega_o t$$

$$f(t) = a_o + \sum_{n=1}^{\infty} (a_n \cos n\,\omega_o t + b_n \sin n\,\omega_o t) \tag{2}$$

Where the coefficients a_n and b_n are determined as follows:

$$a_o = \frac{1}{T} \int_{t_o}^{t_o+T} f(t)\, dt \tag{3}$$

and

$$a_n = \frac{\int_{t_o}^{t_o-T} f(t) \cos n\,\omega_o t\, dt}{\int_{t_o}^{t_o+T} \cos^2 n\,\omega_o t\, dt} \tag{4}$$

$$b_n = \frac{\int_{t_o}^{t_o+T} f(t) \sin n\,\omega_o t}{\int_{t_o}^{t_o+T} \sin^2 n\,\omega_o t\, dt} \tag{5}$$

where

$$T = \frac{2\pi}{\omega_o} \text{ and } \omega_o = \frac{2\pi}{T} \tag{6}$$

T should be a time which encompasses the fundamental frequency of the waveform because f(t) is assumed to be a periodic, continuous function of time with period T.

There is a wealth of literature on the Fourier Series, Fourier Transform, and discrete Fourier Transform (Cooley-Tukey, FFT, etc.), which is covered thoroughly in Refs. 6, 7, and 8. For convenience, useful Fourier relationships as applied to stress analysis will be summarized.

Equation (2) can be represented as shown in Eq. (7),

$$f(t) = \sum_{n=0}^{\infty} c_n \cos\left(n\,\omega_o t + \theta_n\right) \tag{7}$$

where

$$c_n = \sqrt{a_n^2 + b_n^2} \qquad \text{and} \qquad \theta_n = -\tan^{-1}\left(\frac{b_n}{a_n}\right)$$

This is the most useful format for stress analysis as the c_n coefficient gives one-half the peak-to-peak amplitude of any given vibrational frequency. Also, when comparisons are made between different parameters, the angle θ_n will provide phase comparisons at any given frequency, if waveforms have been sampled simultaneously. However, there are limitations. The peak-to-peak value of the waveform itself may be more or less than the C_n coefficient for the fundamental frequency. For example, Fig. 10 contains peak-to-peak amplitudes ranging from a minimum of 8 kpsi to a maximum of 23 kpsi. The first fundamental frequency coefficient (C_{38}) was multiplied by two before plotting was accomplished to obtain 13.5 kpsi. This value corresponds to the peak-to-peak value of the fundamental frequency (750 Hz). Therefore, the frequency spectrum coefficients are essentially weighted averages.

All modern methods of determining Fourier coefficients (a_n, b_n) involve digital techniques and numerical integration by matrix manipulations as indicated in Refs. 7 and 8. Table 2 contains typical restrictions as regards sampling of data 2^n times, frequency range, sample rate and period, and the frequency resolution. These limitations are imposed due to the Cooley-Tukey matrix factorization. This method, or others similar, must be used to reduce large amounts of data within reasonable time periods.

It is sometimes useful to produce power spectra, energy densities, and power density spectra. Some texts refer to the C_n coefficients plotted versus frequency as a power spectrum. To summarize briefly, the Fourier transform of f(t) may be expressed as

$$\mathfrak{F}\left[f(t)\right] = \int_{-\infty}^{\infty} f(t)\, e^{-j\omega t}\, dt = F(\omega) \tag{8}$$

Plotting the $F(\omega)$ versus ω will yield a power spectrum. The energy density (E) is defined as

$$E = \frac{1}{2\pi}\int_{-\infty}^{\infty}\left|F(\omega)\right|^2\, d\omega \tag{9}$$

Also, power density spectrum $[S_f(\omega)]$ has some use with respect to energy within a given band of frequencies. It can be expressed as follows:

$$S_f(\omega) = \lim_{T\to\infty} \frac{\left|F_T(\omega)\right|^2}{T} \tag{10}$$

Table 2. Typical Fourier Analysis Constraints

Integer, N	Number of Samples, 2^n	Number of Spectrum Lines, c_n	Frequency Analysis Range, Hz	Sample Rate, samples/sec[a]	Sample Period, ms	Frequency Resolution, Hz
9	512	256	5,000	10,240	50	19.53 to 20
			10,000	20,480	25	39.06 to 40
			20,000	40,960	12.5	78.12 to 80
			30,000	61,440	8.33	117.18 to 120
			50,000	102,400	5.0	195.31 to 200
10	1,024	512	5,000	10,240	100	9.75 to 10
			10,000	20,480	50	19.53 to 20
			20,000	40,960	25	39.06 to 40
			30,000	61,440	16.66	58.59 to 60
			50,000	102,400	10	97.65 to 100
11	2,048	1,024	5,000	10,240	200	4.88 to 5
			10,000	20,480	100	9.76 to 10
			20,000	40,960	50	19.53 to 20
			30,000	61,440	33.32	29.29 to 30
			50,000	102,400	20	48.82 to 50

[a]An ideal antialiasing filter with a cutoff frequency determined by the frequency analysis range is assumed.

With respect to stress analysis, all of these functions are evaluated using digital techniques within limited time frames. Therefore, T never approaches infinity, and the integrals are over finite time periods. Nevertheless, close approximations are made. For this reason, it is sometimes necessary to average various frequency spectra. This subject is covered in Ref. 9 and will not be addressed in detail. In-depth analysis can involve auto correlations, cross correlations, probability densities, exponential averaging, and various statistical data analysis routines. These methods are used to explain or analyze any anomalies that may occur during jet engine compressor testing.

2.4 FINITE-ELEMENT ANALYSIS AND HOLOGRAPHY

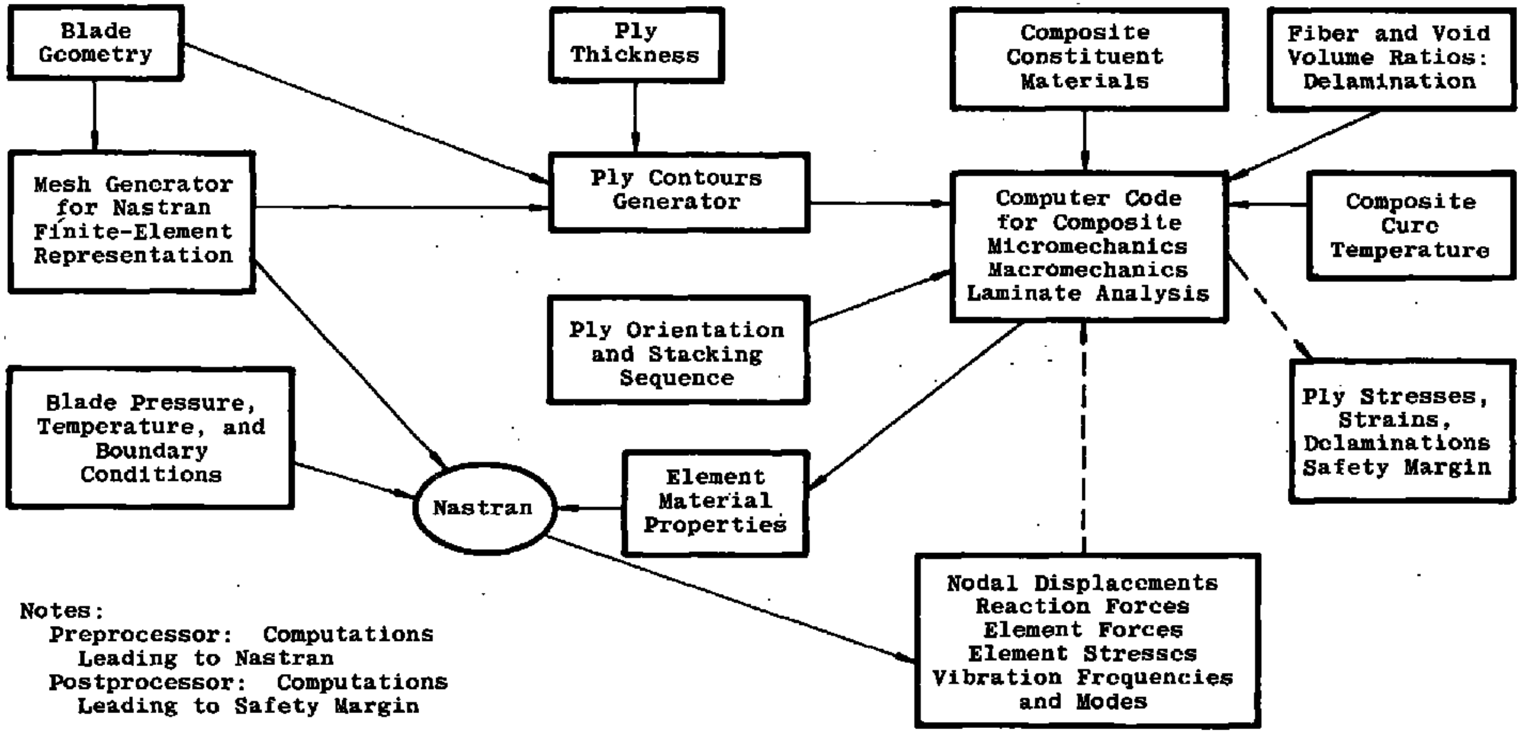
Recent advances in computer technology have made it possible to model complex blade structures mathematically. Math models are useful in making parametric studies, predicting test performance (vibrational modes, peak stresses, fatigue limits, etc.), assessing structural integrity of hardware, and systematically evaluating design modifications. Extensive work has been done in applying these methods to practical problems. Reference 10 describes how the Nastran program (Ref. 11) was used to determine the vibration characteristics of composite fan blades. The results of the Nastran program yield all steady-state forces (aerodynamic pressure/temperature and centrifugal forces), vibration frequencies, and mode shapes of composite blades. Figure 11 shows how this analysis is accomplished with the Nastran program. The results of this analysis were compared to holographic data and found to be in reasonable agreement. It is evident that the recently developed finite element analysis and holographic techniques are two of the most valuable design aids in use today.

Although finite element analysis is the method most recently used in compressor blade design, Ref. 12 indicates that prior methods applying pure pull, moment, and torque loads to junction zones (root, shroud termination zones) in the manner of "black box" transfer functions are still powerful analysis tools. As in the finite element approach, a combination of analysis and precision laboratory experiment is employed.

Further discourse on this subject is beyond the scope of the present report. This information was presented to indicate how analysis techniques influence strain-gage placement, determination of fatigue limits, and online monitoring techniques, as presented in the following sections.

2.5 STRAIN-GAGE PLACEMENT AND DETERMINATION OF OPERATING LIMITS

We will now examine how these various analyses affect the placement of strain gages on compressor blades. Sophisticated bonding techniques and details of strain-gage



(From Ref. 10)

Figure 11. Analysis of fiber composite blade using Nastran.

selection will not be addressed. However, all strain gages are designed, located, and bonded using the following criteria:

1. Gage effect on blade structural characteristics is minimized.

2. Gage effect on aerodynamic aspects is minimized.

3. Gage sensitivity to expected vibrational modes which were determined by the analysis tools indicated in Refs. 10, 11, and 12 is maximized.

Figure 12 depicts a typical strain-gage placement for flexural bending modes. The placement on the concave side of the blade minimizes damage due to impinging air flow. A typical analysis indicates that as the compressor rotor spins at a given RPM, the resultant steady-state stress is approximately 10 kpsi. An analysis using the same methods also predicts the typical stress-strain diagram as shown in Fig. 13. Optimum placement of the strain gage means that the strain gage itself should be subjected to minimum stress while at the same time producing data indicative of the maximum stress levels for any given mode. Unsteady airflow bends the blade and produces oscillatory strain. On side 2, this results in a compressive force which moves the steady-state tensile stress toward zero. However, the previously mentioned analysis methods indicate that side 1 will experience increased tensile stress. The exact point of maximum stress and ratio to the change indicated by the strain gage can also be determined by these analysis techniques. For purposes of example clarity, the ratio was assumed to be one to one. This means that side 1 will experience a peak stress level of 20 kpsi with a minimum level of 10 kpsi at a given RPM. Side 2 experiences a peak stress level of 10 kpsi with a minimum level of 0 kpsi. Peak-to-peak values in each case are identical. This type of information obtained from the various analysis techniques produces the strain-gage transfer function to points of critical stress conditions. This information, coupled with the fatigue endurance diagram (Soderberg relationship, Figs. 5 and 6), and predicted Campbell diagrams, can produce operating limits as described in Ref. 12 for a particular strain gage.* Figure 14 illustrates a typical Campbell diagram and the relationship between relative operating limits and engine speed. It is evident that strain-gage operating limits for a Mode II vibration can increase with engine speed and for a Mode III vibration will reduce with engine speed. Therefore, we may state that operating limits are definitely functions of engine RPM, inlet temperatures and pressures, and strain-gage placement. How this information relates to present day, online analysis techniques will now be discussed.

---

*Operating limits are determined by the transfer function from gage location to points of maximum blade stress. When an oscilloscope is used to display stress, it is calibrated to indicate stress in kpsi, and operating limits are often called scope limits.

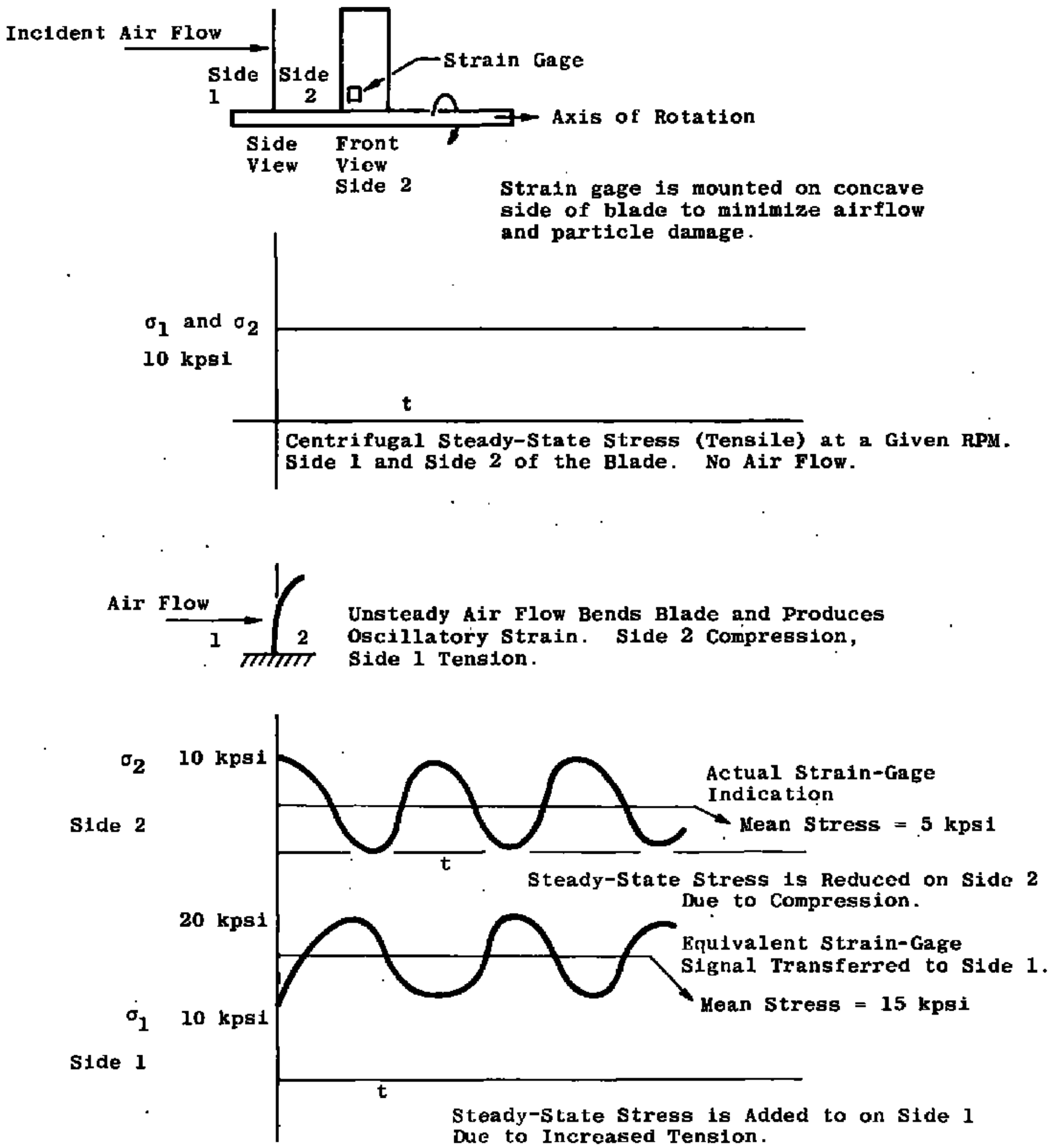


Figure 12. Typical strain-gage placement and strain relationships.

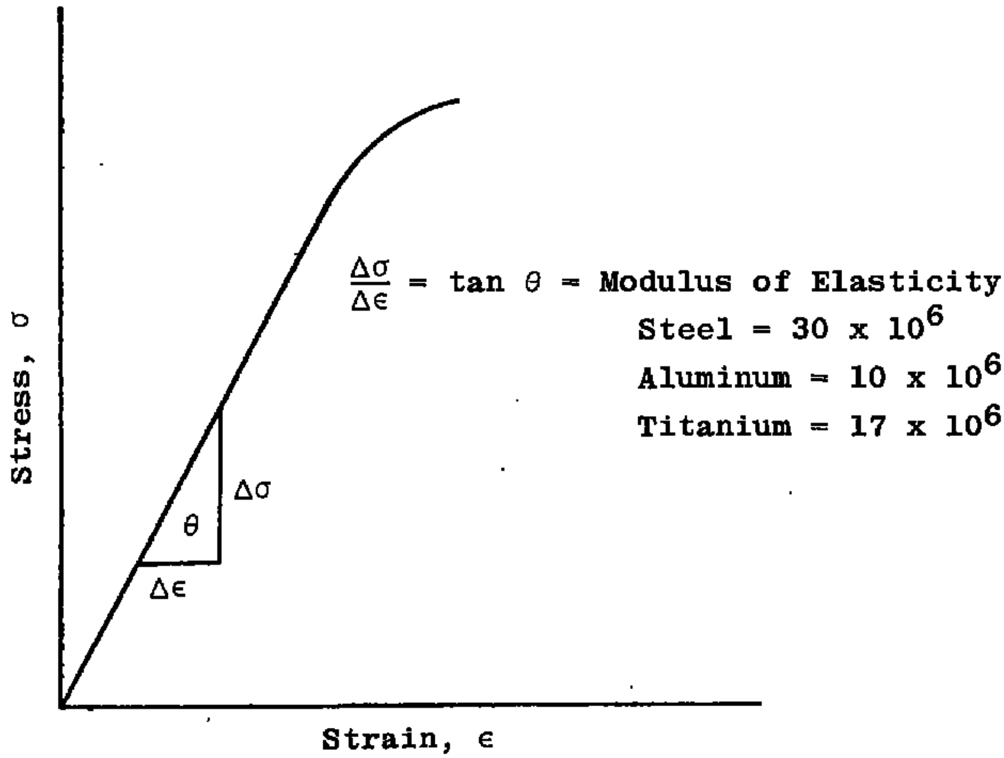
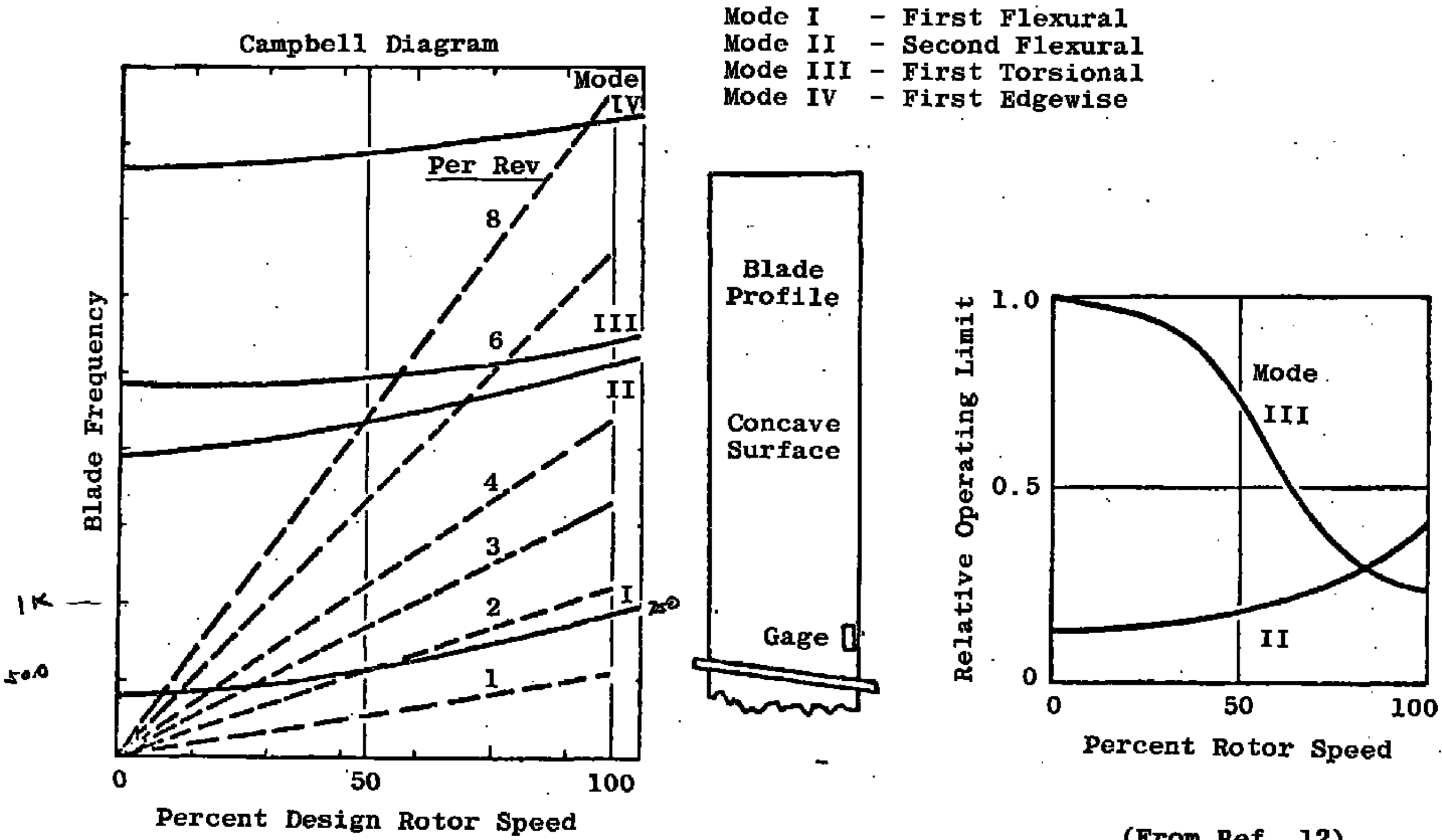


Figure 13. Typical stress-strain diagram.



(From Ref. 12)

Figure 14. Illustrative influence of blade mode coupling resulting in an operating limit increase with rotor speed.

2.6 PRESENT ONLINE MONITORING TECHNIQUES (STRAIN GAGE)

Present monitoring systems consists of oscilloscopes, spectrum analyzers, bargraph displays, and engine performance displays. A bank of oscilloscopes with horizontal sweep produced at a rate equal to the time required for one engine revolution is used to display analog waveforms. One oscilloscope is used per strain gage. The vertical sensitivity is calibrated to read in kpsi per division and is variable for individual strain-gage coefficients. This display allows an operator to mentally compare operating limits with peak-to-peak stress values and also allows a qualitative operator judgement concerning frequency content. A waveform which is stable with respect to the horizontal sweep usually indicates rotor frequency vibrational response. An unstable waveform is usually interpreted as nonrotor frequency stress phenomena such as flutter (Fig. 8).

A manually switched spectrum analyzer is used for frequency analysis. This device is used periodically to check frequency content if a scope waveform is unstable or has exceeded operating limits. It can display amplitude as a function of direct frequency scales or frequency scales that are multiples of the rotor-ordered vibrational frequency.

A bar graph display of peak-to-peak values relative to a single-value operating limit is used to augment the scope displays. The peak-to-peak detection is accomplished with analog peak-to-peak detectors with response times of approximately 87.5 μsec and a fall time to 33 percent in 4.5 sec. This information is sampled digitally (4 samples/sec) and averaged, and the worst case strain-gage indication at any one compressor stage (up to 13) is displayed. Another display indicates stress levels on all gages (up to 21) at any manually selected stage. Elimination of noisy, deteriorating, or open strain gages is accomplished by checking the digitized peak-to-peak data over an arbitrary time period. If the average peak-to-peak level exceeds a prescribed limit, the gage is assumed faulty and deleted from the display. All digitized peak-to-peak data are stored on magnetic tape and transported to a large data processing computer following the test. Observation of these data using an interactive graphics terminal determines key points of interest for further offline analysis of raw analog tapes containing all strain data obtained during testing. These analog tapes were produced by 14-channel, frequency-multiplexed analog tape recorders capable of recording 72 channels of strain-gage data.

An engine performance-type alphanumeric display indicating throttle settings, guide vane positions, rotor speed, altitude, fuel flow, inlet temperature, turbine discharge temperature, etc., is used to augment scope, spectrum analyzer, and bar graph displays. This information is utilized to temper the fixed operating limits used on the bargraph display. As previously described, limits actually change with engine RPM and are affected by inlet conditions. Therefore, the stress observer must mentally weigh the performance information against the scope, frequency spectrum, and bar graph displays to make pertinent and meaningful judgements.

As can be surmised, present online analysis techniques utilize visual display of data for operator observance. There are many disadvantages to this type of operation.

1. Operator fatigue can jeopardize valuable compressors. It is ironic that, over long periods of time, an operator observing fatigue waveforms succumbs to fatigue himself.

2. Critical decisions are limited to human reaction time. A typical sequence of events that might occur during online analysis can be described as follows: Operator observes a bar on the bar graph display exceeding alarm limits (1 to 3 sec). He then observes the oscilloscope display for waveform shape, peak-to-peak value, and stability (1 to 5 sec). If conditions exceed operating limits and the waveform is abnormal, he (she) switches the frequency analyzer into that channel (2 to 5 sec). The frequency spectrum is then observed along with the analog waveform. Diagnosis follows, and a decision is made concerning engine health and the type of vibration involved (5 to 10 sec). The test is then halted, altered, or continued on the basis of this diagnosis. At best, total time required to reach a final decision could be 10 to 23 sec, but operator fatigue could easily double or triple each response time. This reaction time is predicated on the use of highly skilled and trained analysts familiar with the general information presented in the preceding sections. In addition, these analysts must memorize individual operating limits, temperature effects, and engine RPM corrections for each strain gage on the particular engine under test.

3. Online Campbell diagrams (three-dimensional, etc.) and overall stress versus engine RPM are not plotted during an engine acceleration or deceleration. This information could be extremely valuable, as it would provide for direct, on-the-spot comparisons with previously determined laboratory and design analysis plots.

On the basis of this information, it is suggested that further display of data will not provide improvements but will simply complicate an already complex task. To significantly improve upon present online analysis, the actions performed by the highly skilled analyst must be augmented with an automated data processor and analyzer. This can be accomplished by placing pertinent design information, specific details concerning a particular engine, and natural human filtering techniques and anticipatory characteristics into a nonvolatile memory. This memory must then be manipulated using machine-executable algorithms in a manner similar to the methods used by the human analyzer. These algorithmns must be developed with intimate knowledge of stress analyses and man/machine interface methods. This type of approach would provide uniform

analysis, split-second response times, and more sophisticated and intelligent display of pre-analyzed data. These types of improvements could make the difference between determination of an operational boundary and the destruction of a extremely valuable jet engine compressor.

2.7 PRESENT ONLINE MONITORING TECHNIQUES (OPTICAL)

Nasa Lewis Research Center has made advances in optical technology and optical monitoring techniques which should gain wide acceptance within the next five years. Present techniques for mounting and operating optical monitoring systems (Ref. 13), briefly stated, are as follows. A light source is focused on any given compressor or turbine stage as shown in Fig. 15. As the compressor rotates, pulses of light are reflected by each blade as it passes the light source. To distinguish between torsion and bending, four sources of information are utilized:

1. Reflection from blade trailing edge (reference for torsional stress).
2. 1/rev sensor (reference for blade identification).
3. 1/blade sensor (reference for bending stress).
4. Midchord reflection pulse (compared with the three previous references, gives torsional and bending mode information).

The delta time between references and midchord reflection pulse is proportional to the amount of nonrotor-ordered stress. This system has proved to be an excellent flutter detector when coupled with an oscilloscope display as indicated in Fig. 15. Pulse conditioning and interface electronics to the oscilloscope and also for future interface to a digital computer are covered in Ref. 13.

This method of vibrational observance provides information on all blades of any given compressor stage and thus has a substantial advantage over current electromechanical systems. Present disadvantages include:

1. Lack of frequency information with respect to all vibrational modes (engine and nonengine ordered).
2. Inability to record data in a digital format for more exact analysis, online and offline.

These disadvantages are being addressed, and suggested methods of improvement are indicated in Ref. 13. In addition, an AEDC research program is providing a software and hardware system which utilizes NASA-Lewis sensor electronics and eliminates these disadvantages.

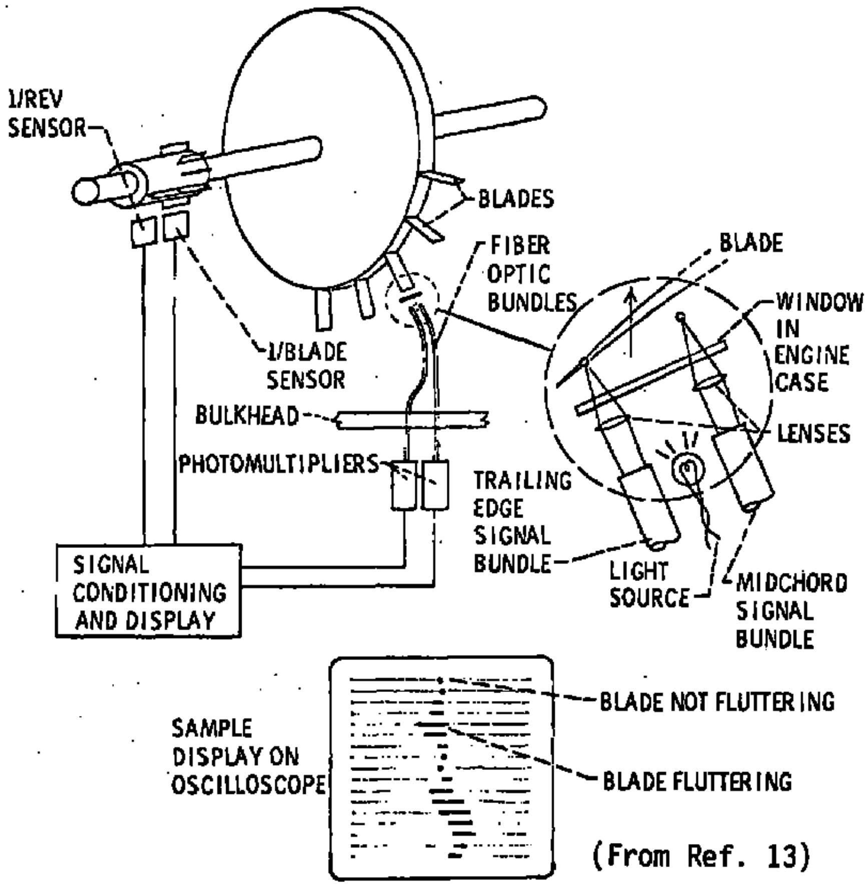


Figure 15. Photoelectric scanning system (PES) elements.

It appears that a state-of-the-art online monitoring system must include the capability of observing, recording, and analyzing the data produced by optical detection systems while observing strain-gage signals. Furthermore, it appears likely that selected strain-gage information processed with synchronously obtained optical data will be the optimum means of online analysis in the future.

2.8 PRESENT OFFLINE ANALYSIS TECHNIQUES (STRAIN GAGE)

Current offline analysis includes the following:

1. Production of various kinds of Campbell diagrams as indicated in Figs. 16 and 17 for all strain gages producing meaningful data at any given time.

2. Production of overall stress diagrams (peak-to-peak) versus engine speed as indicated in Fig. 18. These would be used in conjunction with data presented in Figs. 16 and 17.

3. Production of a single-frequency spectrum and its corresponding analog time domain waveform as shown in Figs. 9 and 10. This could be one frequency spectrum of significant interest taken from the family of spectra shown in Fig. 17.

All of the above information is produced to verify engine integrity over all operating conditions and for comparison with data previously obtained from design analysis and laboratory experiments.

2.9 PRESENT COMPRESSOR DESIGN AND VERIFICATION PROCEDURES

A brief summary of present design procedures will be helpful in relating previous information to its use in preliminary design and analysis, testing and design verification, and final acceptance of the design product. The primary basis for this summary encompasses Refs. 2, 10, and 12. Briefly, present design procedures are as follows.

1. Produce operational specifications

    a. Inlet conditions range (pressure, temperature, air loading, etc.)

    b. Inlet atmospheric conditions range (moisture, dust, foreign matter, etc.)

    c. Rotor rpm (centrifugal forces)

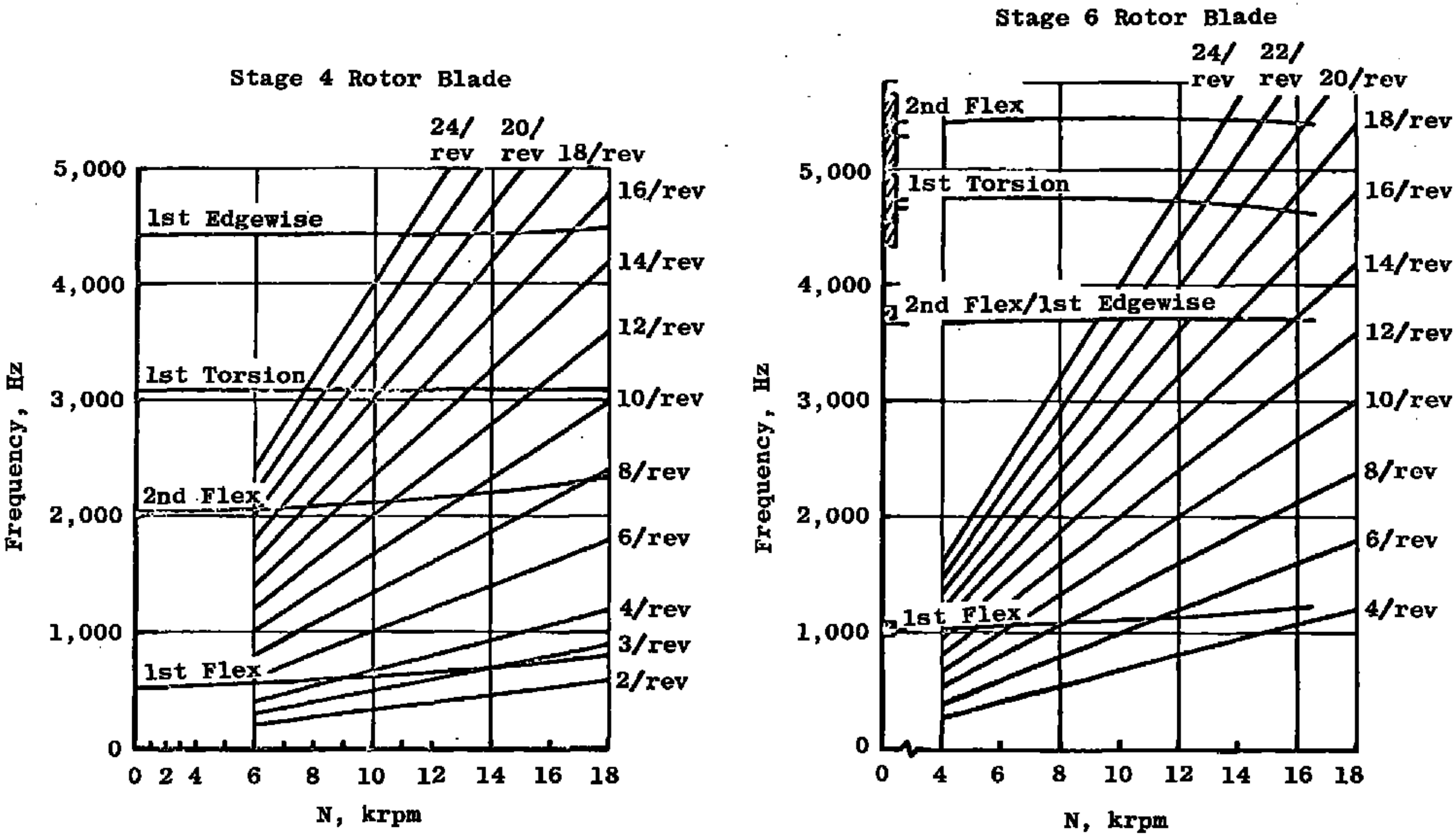


Figure 16. Typical Campbell diagrams.

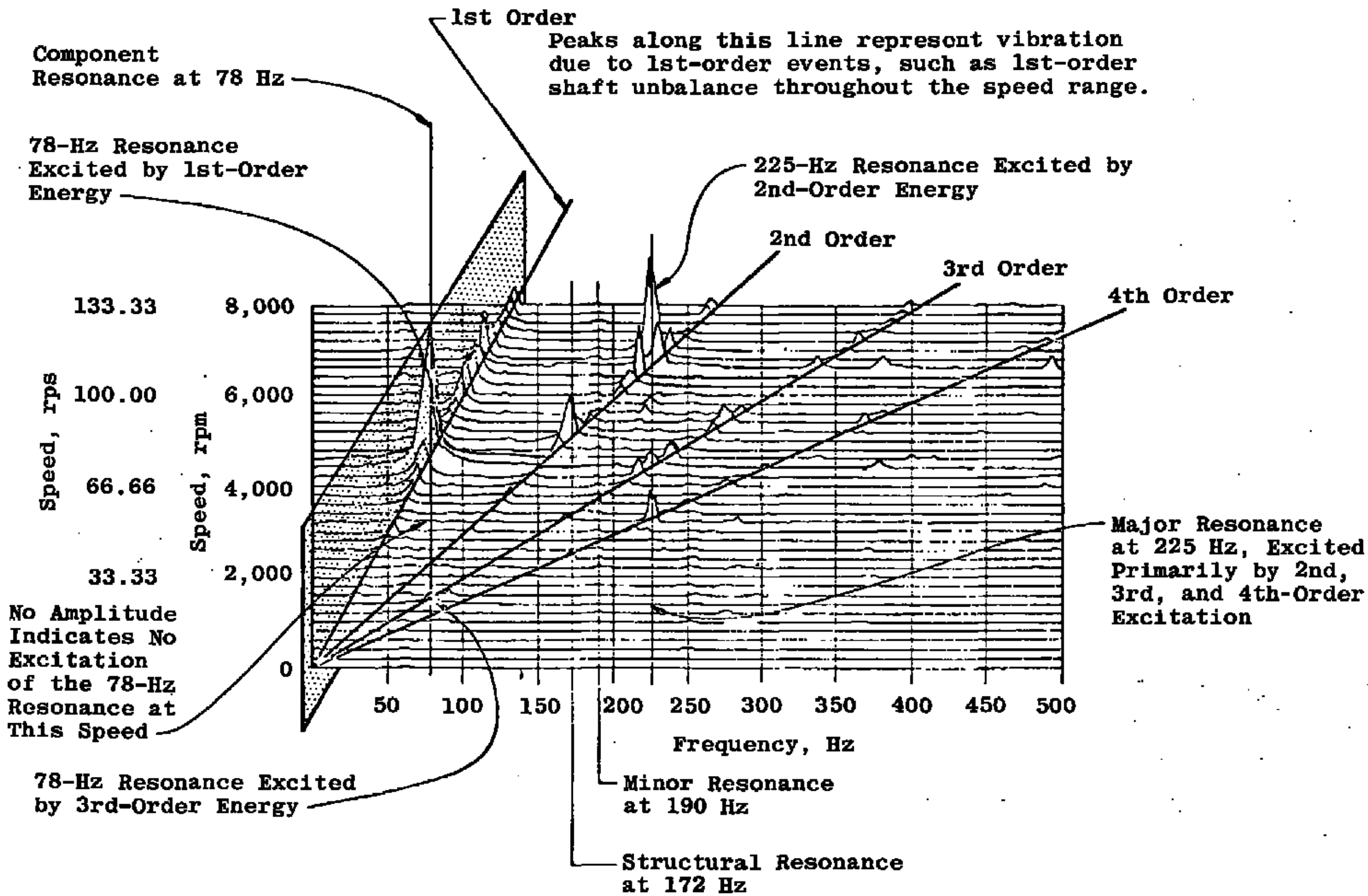


Figure 17. Typical Campbell diagram (three-dimensional).

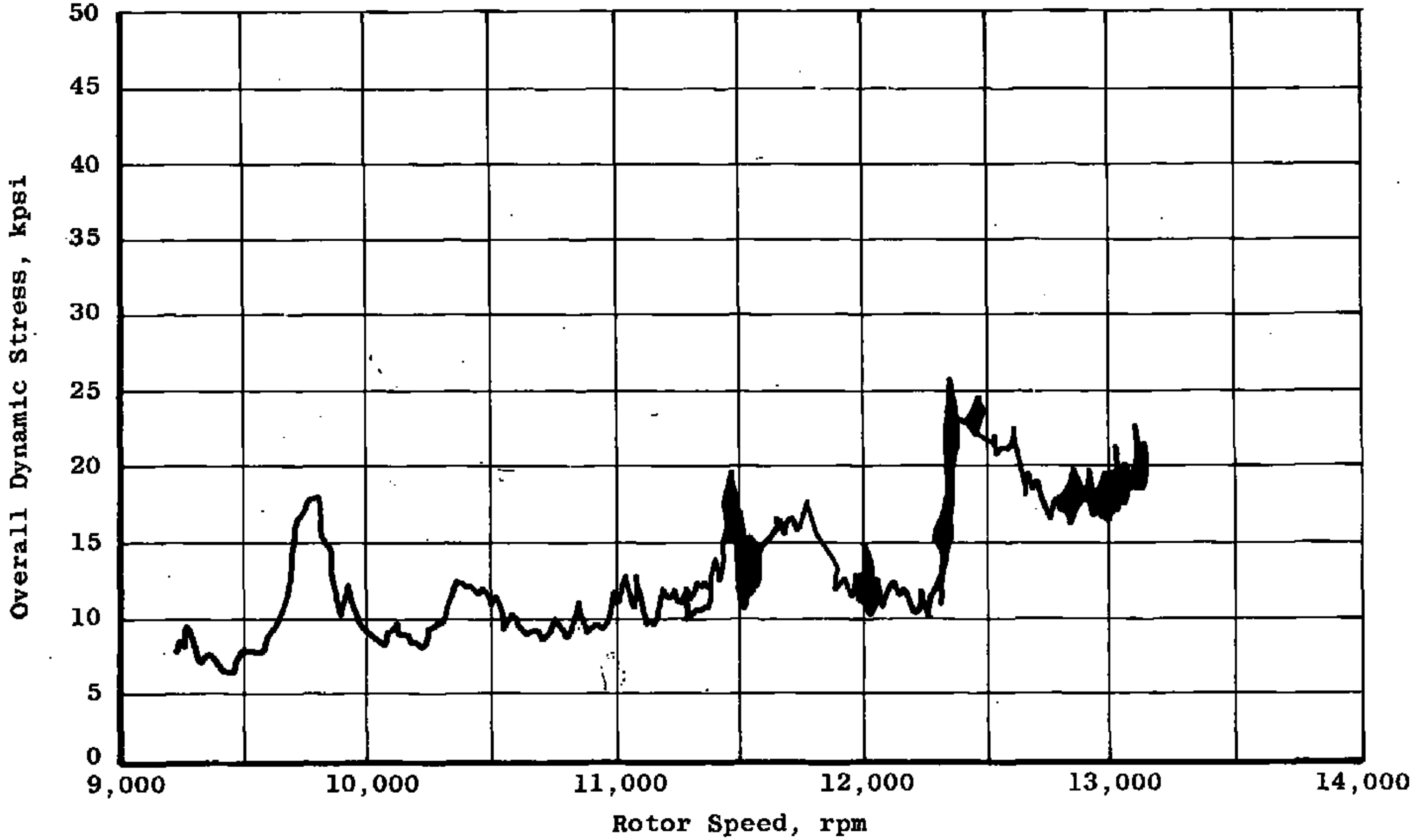


Figure 18. Typical overall stress versus rotor speed display from posttest data editing system.

2. Determine compressor operational limits

   a. Produce preliminary blade designs.

   b. Determine vibrational and steady-state force characteristics (maximum to minimum vibration stress, fatigue limits, and areas of instability) of the blades using Nastran or equivalent finite-element analysis procedures, or the "black box approach," using pure pull, moment, and torque loads.

   c. Perform laboratory bench tests using strain-gage and holography techniques. Compare results with finite-element analysis or other analysis techniques. Determine blade resonant frequencies for all these vibrational modes. Make Campbell diagrams showing vibrational modes relative to rotor speed.

   d. Determine optimum points for strain-gage placement based upon laboratory, finite-element analysis, and "black box" analysis results. Utilize points of minimum stress and physical degradation of strain gage. Maximum stress points are given by transfer function from strain-gage contact point.

   e. Determine gage sensitivity ratio for each strain-gage location and calculate operating limits versus rotor RPM.

3. Perform composite test with rotor, rotor blades, and stator blades over predicted operating curve (inlet guide vane angle versus engine speed). Perform off-schedule tests and determine performance margins.

4. Produce offline, after-test Campbell diagrams and peak-to-peak stress values versus rotor speed diagrams. Compare this information to design analysis (output from Nastran, etc.) and laboratory observances. Resolve discrepancies and redesign if warranted.

The requirements for an improved online analysis system will now be stated on the basis of the presented information. Producing significant improvement over present online analysis techniques requires a system which can 1) imitate the present desirable human operator functions and 2) add capability which the human operator does not have.

3.0 REQUIREMENTS FOR AN IMPROVED ONLINE MONITOR SYSTEM

General overall system requirements will be stated first. These hardware and software requirements are based upon the experience gained in recently completed test programs and the design and analysis methods presented in Section 2.0. These data indicate that future systems must be both flexible and expandable. The hardware and software used to satisfy increasingly complex test requirements must provide for quick and easy adaptation to changes from year to year. The author believes that the requirements as stated will satisfy present and future test needs (up to 10 years).

3.1 CONCEPTUAL CONSTRAINTS

The system must be extremely flexible, modular, and "upward compatible" with respect to hardware and software. The term software is used because it will be virtually impossible to meet the requirements as stated without using a computer. All software furnished must be modular and utilize structured programming techniques.

For example, a computer central processing unit (CPU) with a basic cycle time of 2 μsec for register mode operations and 28 K of memory may satisfy minimum or present requirements. However, future or maximum requirements may dictate a CPU with 1-μsec cycle times and a 128K memory. All software written for the old CPU and memory must be capable of running on the new machine and memory along with new modular software that would be developed for future requirements. In addition, all other components of the old system must be directly compatible with the new system components. These requirements must hold true for all system components whether they be front-end input-output (I/O) gear, array processors/Fourier analyzers, etc., line printers/plotters, or command terminals, and of course all system software modules.

3.2 HARDWARE INPUT REQUIREMENTS: ONLINE, REAL TIME

Requirements follow for four types of inputs:

1. Group I inputs will accept strain-gage analog input signals that have been conditioned for recording on FM analog tape. This is the present means of recording analog strain signals.

2. Group II inputs would functionally replace Group I in the future, as the change becomes feasible. The same information would be recorded using digital pulse code modulation (PCM) techniques. This means that each channel would be multiplexed and digitized, and a PCM data stream recorded. Input electronics to the analysis system would capture data of

interest in the PCM stream and input data in a manner similar to the analog multiplexing methods required using Group I inputs. The PCM input should be considered a future capability and would be added to the system as the cost, reliability, bandwidth, and channel capability improve.

3. Group III inputs will accept data produced by the optical online analysis techniques described in Section 2.0.

4. Group IV inputs will accept 32 channels (minimum) of lower bandwidth data for such parameters as rotor speed, IRIG time, engine guide vane angles, oil pressures, etc.

A practical, cost-effective system evolution could be as follows:

1. Produce first system with Group I and IV inputs only.

2. Add Group III inputs to include optical techniques which will be developed within the next two to five years.

3. Replace Group I inputs with Group II input capability if future technology developments prove this capability to be cost effective.

3.2.1 Group I Input Requirements

1. 16 to 160 strain-gage channels (analog) recorded on FM tape recorders and simultaneously input to the analysis portion of this system with input specifications as follows.

   a. Bandwidth:
      0 to 30 kHz

   b. Voltage levels (input capability, each channel):
      0 to 0.225 volts RMS or ±0.32 VDC
      0 to 0.45 volts RMS or ±0.64 VDC
      0 to 0.9 volts RMS or ±1.28 VDC
      0 to 1.8 volts RMS or ±2.56 VDC

   c. Resolution:
      1/2,047 + sign (11 bits + sign)
      12 bits, 2's complement

For example:

The 0- to 1.28-v scale has a resolution of 0.625 mv

Dynamic voltage range = 20 log V_1/V_2 = 20 log 1.28/0.625 mv = 66.22 db

Dynamic power range = 10 log P_1/P_2 = 10 log $(1.28)^2/(0.625\ \text{mv})^2$ = 66.22 db

(These conditions given on the assumption that $P = V^2/R$ and that the voltages are produced across identical R's.)

d. Overall Uncertainty: 0.5 percent ± least significant bit (LSB)

2. 16 to 160 stain-gage channels (analog peak-to-peak detectors) simultaneously input with the raw analog signal with specifications as follows:

a. Bandwidth: 0 to 30 kHz

b. Voltage levels: same as previously stated.

c. Resolution: same as previously stated.

d. Attack time: 0 to 500 μsec, variable (nominal 10 μsec)

e. Hold time: 90 percent of peak value 0 to 50 msec (nominal 10 msec)

f. Overall Uncertainty: 0.5 percent ± LSB

3.2.2 Group II Input Requirements

1. 16 to 160 strain-gage signals (discrete).

This capability would be in lieu of Group I inputs. Each channel would be digitized (11 bits + sign) 2's complement at a rate consistent with 30- kHz bandwidth requirements. All channels would be recorded on pulse code-modulated (PCM) tape recorders or formatted and stored on megaword high-speed bulk memories or disk packs. Ping-pong recording methods must be used to provide limitless storage. Multiplex electronics would be provided for random selection of various channels for input of this high-speed data stream to the computer. This interface and its control electronics would behave as an equivalent FM multiplex analog recording system and its interface to this system.

2. Peak-to-peak detectors.

   Peak-to-peak detection must be accomplished by all systems and may be either digital or analog; however, the end result should be a digital word (at least 12 bits) indicating the peak value. This could be stored on PCM tape, bulk memory, or bulk disk. All requirements stated for Group I inputs must be met by any digital recording and input system.

3.2.3 Group III Input Requirements

Group III input requirements would consist of 1 to 20 optical data signals (digital), as follows:

1. Each data signal would be comprised of three 4- to 16-bit digital words updated at the rate of three new words every 30 to 240 μsec.

2. Each word would represent a delay time between a reference signal and a reflected data signal ranging from 0.01 to 20 μsec with 4- to 16-bit resolution.

For example: A 20-signal system would be capable of accepting sixty 4- to 16-bit words and reading all 60 words every 30 to 240 μsec. Accuracy would be determined by the preconditioning electronics prior to production of the digital word. This aspect is being developed in various research programs and need not be considered a part of this system. The software which analyzes the difference in word values is also being developed. This system should be capable of accepting such software, which may require up to 32K words of memory. Execution times for this software could range from 1 msec to 1 sec, depending on sophistication.

3.2.4 Group IV Input Requirements

Group IV input requirements would consist of a minimum of 32 analog inputs with specifications as follows:

1. 0- to 1-kHz bandwidth. (The majority of inputs will be 0 to 50 Hz or less, but capability should be provided for 0 to 1 kHz.)

2. Voltage levels: as given for Group I

3. Resolution: as given for Group I

4. Overall accuracy: 0.5 percent ± LSB

These inputs are to be used for various engine conditions that can affect operating limits such as engine speed, guide vane angles, inlet conditions, etc. In addition, this information must be recorded in a manner similar to time and frequency/domain data. This will be described in the analysis section (3.4).

3.3 CALIBRATION OF ALL INPUTS

The system shall be capable of self-calibration on all channels. This shall consist of inputting at minimum a 2-point calibration voltage and system calculation of the slope and intercept for the equation $y = mx + b$, where y = engineering unit data, x = raw counts, m = slope, and b = intercept.

Load equivalents will be input via a command terminal. Otherwise, all operations would be automatic. Capability for expansion to a 6-point calibration system and piecewise linear or cubic engineering unit equations should be considered a maximum requirement but need not be implemented immediately.

3.4 ANALYSIS REQUIREMENTS: ONLINE, REAL TIME

Two analysis modes will be described:

1. Automatic analysis per preconceived test plan (time and frequency domain).

2. Analysis per a set of predetermined operator-initiated commands (instant replay of past events or manual monitoring of current events).

Automatic analysis should be the normal and most used mode. It will essentially imitate the present analysis methods that are described in Section 2.0.

To implement the automatic analysis mode, one must input the following data to the online analyzer prior to test.

1. Operating limits, as defined in Section 2.0 and Fig. 14. Limits would be digital with a minimum number of 20 per strain gage. For example, an engine with a top speed of 300 rev/sec (18,000 rpm) would have a minimum of 20 scope limits spaced at 0, 15, 30, 45, . . . etc., to 300 rev/sec. The maximum number of limits would be 100. This means that a 160-channel system would have a minimum of 3,200 and a maximum of 16,000 limits. These limits would be modified to reflect rotor RPM and inlet pressures as required.

2. Frequency limits similar to operating limits. Limits can be a function of frequency and another parameter such as inlet pressure for a given gage. Minimum requirements would be at least 5 limits per channel with linear interpolation between points. Maximum requirements derived from FFT limitations would be 1,024 limits per channel with no interpolation required. For example:

   A 5-limit/channel system would require 5 x (160) x 2 = 1,600 16-bit words for limit statement.

   A 1,024-limit/channel system would require 1,024 (160) x 2 = 327,680 16-bit words for limit statement.

3.4.1 Summary of Time and Frequency Domain Analysis

Time and Frequency Domain Analysis is summarized in this section with details presented in sections 3.4.2 and 3.4.3.

1. The Time Domain System acquires data on up to 160 channels and extracts peak-to-peak data at least every 10 msec. Also, within a 100-msec time period, worst case analysis on averaged data takes place and the 16 worst case channels are selected for display and for a command input to the Frequency Analysis System. In addition, recordkeeping takes place to eliminate bad strain channels and to maintain a cyclic record for a given strain limit.

2. The Frequency Domain System accepts the 16-channel command and produces a frequency spectrum and frequency limit check on all 16 channels. Worst case analysis is performed, and this channel is displayed on a high-speed oscilloscope along with limits and the analog waveform itself. In addition, autoranging with respect to frequency analysis can be utilized if one desires. In both cases the data is stored on mass storage devices for future use.

3.4.2 Time Domain Analysis

The peak-to-peak value of each waveform will be determined, digitized, and stored at least once every 10 msec on 16 to 160 channels. The analyzer should be capable of averaging 2 to 16 consecutive samples on each channel and storing the results on a high-speed mass storage medium. Initial minimum storage requirements would be 20 million 16-bit words. For example, a 160-channel system would peak-to-peak detect and

digitize all 160 channels every 10 msec. This would produce 160 words/10 msec = 16,000 words/sec. If the average were not taken, the length of time required to fill the storage medimum would be 20 x 10^6/16 x 10^3 = 1,250 sec = 20.83 min. If 16 consecutive samples were averaged, the storage time would be 16 x 20.83 = 333 min = 5.55 hr. The maximum transfer rate would be determined by the nonaveraged example. Transfer rate = 1/(16,000 words/sec) 2.5 x 10^{-6} sec/word = 62.5 μsec/word. At present, mass storage devices are available with transfer rates of 3.31 μsec/word or less.

Online analysis of these digitized peak-to-peak values shall take place at least every 100 msec, as follows:

1. Perform worst case analysis on all 160 channels. Determine the 16 channels that are either exceeding their scope limits by the maximum delta or approaching the limit with minimum delta.

2. Use these 16 channels for display purposes and also as a selection command to a frequency domain analyzer. The frequency analyzer would automatically select the 16 stated channels for further analysis. The channels displayed would be updated once per second. However, altering of channels should be limited to once every 10 sec. This should be a variable determined by user preferences.

3. Maintain a record of how many times each channel exceeds the scope limit. If this limit is exceeded by more than a changeable/programmable value, the analyzer could automatically eliminate the channel from the analysis scan. This mode could be used for two purposes:

    a. Maintaining a flex cycle record of the number of times a given blade has exceeded scope limits. (See Figs. 3 and 4.)

    b. Elimination of faulty strain gages (open or noisy). The analyzer would print a record of such changes, giving time and other parameters that may be pertinent.

It should be emphasized that these are minimum requirements and as such can be expanded to include greater storage capability, faster cycle times, more record-keeping capability, and more sophisticated storing and worst case analysis algorithmns.

3.4.3 Frequency Domain Analysis

The 16 channels selected by the time domain analysis will be further analyzed in the frequency domain. Minimum analysis would require a scan of all 16 channels every 2

sec. Minimum capability would allow the sampling of two channels simultaneously with 512 Fourier spectrum lines produced for each channel as described in Section 2.0. Minimum frequency range on all channels would be 30 kHz, but the capability to analyze 0 to 10 Hz to 0 to 150 kHz should be included. It is desirable to be able to sample all 16 channels simultaneously. This would imply an overall sample rate of 16 x 2 x 150 kHz = 4.8 MHz. Even though this is possible with today's technology, the cost is extremely high. Therefore, preliminary cost trade-off analysis indicates that a basic sample rate of 300 to 600 kHz will suffice for the present. The 600-kHz rate would allow for simultaneous sampling of 10 channels (10 x 2 x 30 kHz = 600 kHz) with a 300-kHz bandwidth and two channels (2 x 2 x 150 kHz = 600 kHz) with a 150-kHz bandwidth. These calculations assume perfect antialiasing filters: if the filters are not perfect, the factor of two must be adjusted accordingly.

Analysis would include producing the Fourier a_n and b_n coefficients, from which the c_n coefficient and θ_n (phase angle) must be calculated. Analysis would include selection and ordering of all channels on a worst case basis. The worst case channel would automatically be displayed on a high-speed oscilloscope display which would be updated each time a new analysis occurred. The oscilloscope display should include frequency spectrum, associated frequency limits, and the analog representation of the waveform on the worst case channel. In addition, the ability to ensemble or exponential average consecutive scans of all 16 channels is required. Any number of averages 2 to 16 should be available. These raw spectrums or ensemble averages should be stored on a 20-megaword mass storage medium with at least 3.31 μsec/word transfer times as indicated for the time domain system. For example, one scan (nonaveraged) would produce 16 (512) x 4 = 32,768 16-bit words every 2 sec. This means that storage time would be limited to 20 x 10^6/16,384 = 1,220 sec = 20.34 min.

$$\text{Transfer rate} = 32{,}768 \text{ words/2 sec} = 16{,}384 \text{ words/sec}$$

$$\text{Transfer time} = \frac{1}{16{,}384 \text{ words/sec}} = 61.04\ \mu\text{sec/word}$$

Ample provision for average access times and overhead setup is provided. In addition to this basic frequency analysis and storage, the system should be capable of auto-frequency ranging. This would consist of checking for data in the 0- to 30-kHz range and changing the analysis range automatically if no data below an arbitrary limit appears. Typical ranges would be as shown in Table 3. Note that a frequency range of 0 to 150 kHz is included. Even though the basic frequency of any one channel will not exceed 30 kHz, there is a requriement to sample at least four channels simultaneously. This means that the sampling rate must be at least 245.76 kHz (assuming a 2.048 sample factor).

Table 3. Frequency Analysis Range

Steps	Basic Range 1, 0 to 150 Hz[a]	Basic Range 2, 0 to 1,500 Hz[b]	Basic Range 3, 0 to 15 kHz[c]	Basic Range 4, 0 to 150 kHz[d]
1	0-10	0-100	0-1	0-10
2	0-20	0-200	0-2	0-20
3	0-30	0-300	0-3	0-30
4	0-40	0-400	0-4	0-40
.				
.				
.				
15	0-150	0-1,500	0-15	0-150

[a]Steps of 10 Hz

[b]Steps of 100 Hz

[c]Steps of 1,000 Hz

[d]Steps of 10 kHz

Specifying a minimum limit of 307.2K samples per second will achieve sampling of five channels with a 30-kHz bandwidth. This also provides for, if necessary, the sampling of one channel at 307.2 kHz or a 0- to 150-kHz spectrum. All channels are to be preceded by antialiasing filters capable of providing the correct cutoff for the desired analysis range consistent with the classical sampling theorem. In addition to this, the capability to apply weighting functions such as Kaiser Bessel, Hanning, Hamming, and Gaussian must be included. For the purposes of stress analysis, it appears that the Kaiser Bessel may be the best overall weighting (Ref. 8).

3.4.4 Instant Data Replay

This requirement will entail two modes of data replay:

1. Display of data recorded by the time and frequency domain system on mass-storage disk packs.

2. Further analysis by operator-demanded replay of the raw analog tapes or PCM tapes back into the system front end with analysis on any one channel or group of channels emphasized. An alternative would be observing raw data signals (real-time) which, in essence, would be a manually controlled system. This requirement can be met by supplying various operator command modes for selecting channel number, time, etc. for a particular parameter (time or frequency information). Data plots on a conventional plotting scope such as Tektronix, Grinnel, or similar systems would then be provided. Figures 9, 10, 16, 17, and 18 indicate typical plot formats for frequency and time domain information. Capability for scale change, labeling, etc., must be provided by simple (1 to 15 stroke) operator keyboard commands.

Typical response times for producing such plots from disk-type data should be less than 10 sec. Average response times for producing plots from analog tape would be identical with the addition of tape search times. For data recorded within the previous 5 min. of testing, this should be less than 2 to 3 min., assuming a fast search mode is available. Note that automatic analysis as previously described could be suspended during this operation; however, atuomatic analysis should be resumed within 5 to 10 sec after this operation has been completed. Hard copy capability must be provided for any plot produced on a CRT screen. This could be a high resolution line printer/plotter or a hard copy unit used with various CRT displays. In either case, resolution of CRT and copier must be compatible. Overall resolution should be adequate for providing plots equal in appearance to Figs. 16, 17, and 18.

3.5 FUTURE SYSTEMS ANALYSIS CAPABILITY

In the future it should be possible to produce a diagram of overall stress versus engine RPM during an engine acceleration or deceleration on 1 to 16 channels of data (see Fig. 18). In automatic mode, this would take place on all channels selected as worst case by the Time Domain Analysis System, at the beginning of a speed change. An operator or observer should be able to select alternate channels prior to start. Future capabilities should also include the production of an overall frequency spectrum as shown in Fig. 17 on at least one channel during an engine acceleration or deceleration. The Frequency Analysis System would choose a worst case channel and sense the beginning of an engine speed change. However, manual override should be provided for selection of any channel. The two plot modes referred to would occur simultaneously with automatic analysis as previously described.

The stress analysis system must be capable of interfacing to an automatic control system. The automatic control of an entire sequence of events with respect to engine speed, inlet guide vane angles, inlet temperature, and pressure (Mach number, etc.) and monitoring of critical engine parameters such as oil pressure and temperature is planned for jet engine test cells at AEDC. Such systems will be developed from the automatic control systems which are now in use for solid and liquid rocket testing. This same capability adapted to jet engine testing would afford a complete, predetermined test schedule for such things as corridor clearing tests and off-schedule performance limit tests. The stress analysis system would provide vital information to the control system concerning flutter, stall, and other abnormal conditions. The control system would use this information to stop a test or place the engine in a safe operating mode. An operator or the control system itself would proceed to the next planned condition or critical operating point.

Offline analysis would include plotting as previously mentioned in the first paragraph of this section but would offer more extensive analysis capability such as:

A. Cross-spectrum
B. Transfer function
C. Coherent output power
D. Inverse Fourier transform
E. Auto correlation
F. Cross correlation
G. Convolution
H. Signal averaging
I. Probability density histogram
J. Probability distribution
K. Coherence

In addition, a CRT terminal and hard copy unit would be provided for making report quality plots. The plots produced online and during instant replay could also be report quality, but time constraints will limit resolution. This mode of operation should produce plots as quickly and easily as the online or instant replay mode, except for added resolution capability and operator control.

4.0 CONCEPTUAL DESIGN OF AN IMPROVED ONLINE ANALYSIS SYSTEM

The design appraoch is as follows:

1. Utilize all means of data conditioning and recording equipment which presently exist at AEDC.

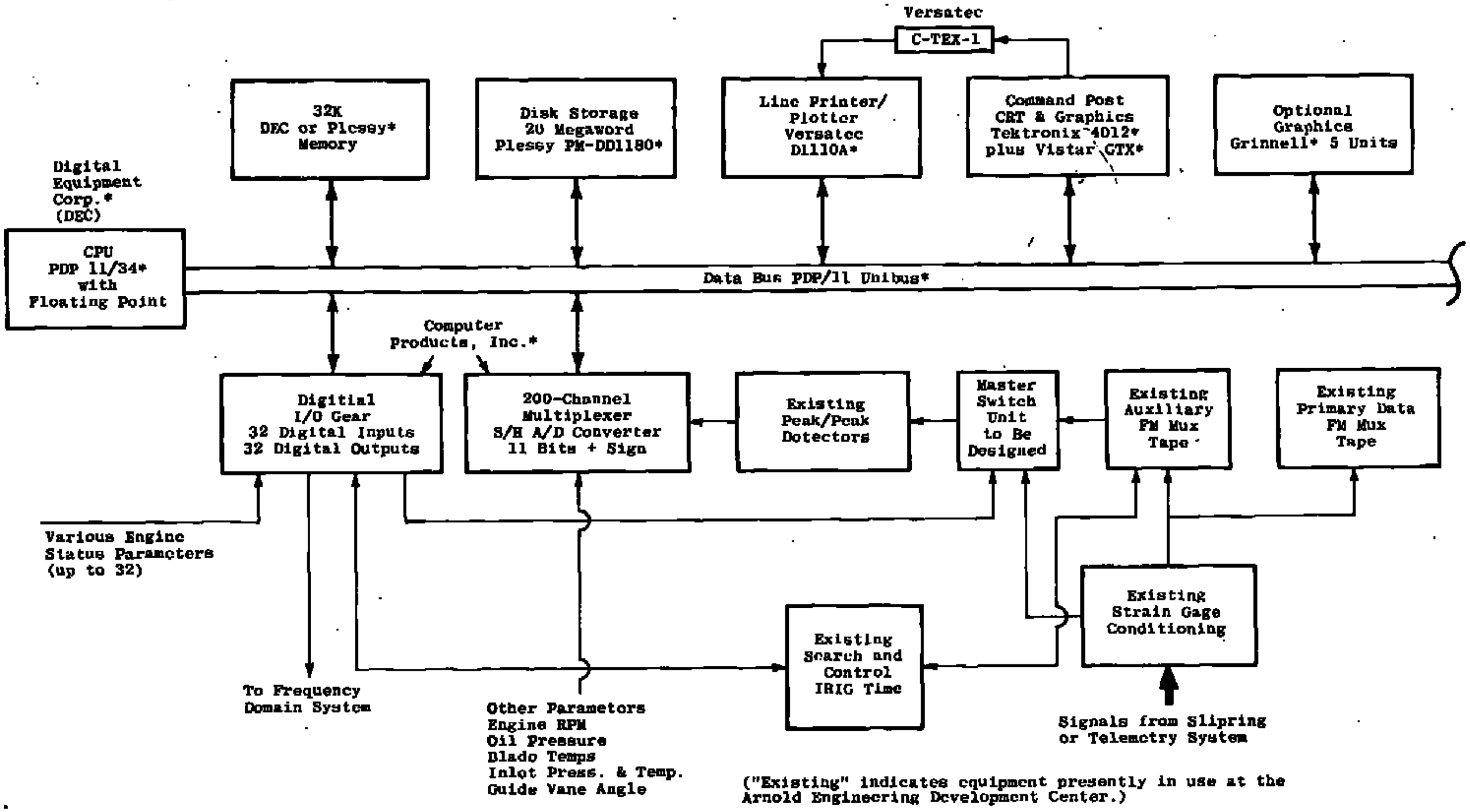
2. Add to this basic equipment as necessary to satisfy minimum requirements as stated in Section 3.0 while optimizing the cost/capability ratio.

3. Design this system to allow expansion to future capability and maximum requirements as stated in Section 3.0 with minimum expansion cost and implementation problems.

After a basic System I design is produced, the system is to be expanded (System II, System III) to demonstrate expandability concepts, which provide optimum system development with respect to future work. Modularization of all system hardware and software is considered to be extremely important. This design technique separates the system into a manageable group of functions (time/frequency) which work together to satisfy overall specifications.

4.1 TIME DOMAIN SYSTEM I

The proposed Time Domain System is depicted in Fig. 19. Conditioned strain-gage signals are fed into a Master Switch Unit, Primary Data Mux Tape, and Auxiliary Data Mux Tape. For purposes of simplicity, the Auxiliary Tape will be assumed to have all demultiplexer electronics necessary for playback of all channels simultaneously. The tape search and control unit, controlled by the digital I/O gear, could thus provide automatic control of the rewind, fast-forward, record, and playback modes. This, coupled with the master switch unit control, would provide for instant data replay capability direct from FM tape into the peak-to-peak detectors. It would also provide for direct observance of strain signals for time domain analysis in the automatic mode described in Section 3.0. The peak-to-peak detectors will possess specifications as indicated in Section 3.3 and will utilize existing AEDC-designed analog detectors. The 200-channel multiplexer (MUX) system is broken into three parts. Two 80-channel systems with a basic sample rate of 20 kHz each satisfy Group I input requirements. Group IV requirements will be satisfied by



*Or equivalent hardware and software compatible with the chosen CPU.

Figure 19. Proposed time domain system I.

adding another 40-Channel MUX (of which 32 channels would be used and 8 would be spare) with a basic sample rate of 20 kHz. The CPU, memory, and disk storage will handle analysis and data storage requirements (Section 3.9). The line printer/plotter and command post will provide software development capability and simultaneous graphic display of time domain data with critical alphanumeric data/messages. The optional graphics unit could be used for lower resolution graphic displays and additional alphanumeric data displays.

4.1.1 Timing Considerations on Sampling of Data

Eighty channels will be sampled at a rate of 20 kHz (1 sample/50 μsec = 80 samples/4 msec). Both 80-channel MUX's working in parallel on an interrupt basis could produce a sample of all 160 channels in 4 msec. Also, the other 40-channel MUX would have produced a sample on all 32 engine-related parameters in the same time period (192 samples/4 msec = 48,000 effective samples/sec). Expansion to 60,000 samples/sec is possible. (See Fig. 20 for sampling format and core map.) This information could be direct memory accessed (DMA) into memory, thus saving CPU time.

4.1.2 Data Acquisition and System Software

Please refer to Figs. 20 and 21 for the following discussion. As indicated by the specification (Section 3.9), it is desirable to average up to 16 consectuvie scans. Therefore, 16 x 4 = 64 msec would be available to obtain the data. Total core required would be 200 x 16 = 3,200 words. Averaging time would be time required to do 160 x 16 = 2,560 additions (ADD) and 5 x 160 = 800 arithmetic shifts right (ASR). Using a DEC 11/34 CPU as a time base reference would have required 3 μsec per ADD and ASR. Total time = 10 msec.

Assume operating limits have been input and converted to integers (12 bits) per latest calibration data. This requires 3,200 words of core for limit storage, assuming 20 different sets of limits for 20 different engine RPM ranges. Selection of limits requires less than 1 msec. Worst case analysis (Fig. 22) consists of calculation of deltas = average values minus limits. A comparison algorithm for determining 16 worst case channels is then executed. Proper logic for cyclic record keeping and elimination of bad strain channels is executed. The sixteen worst case channels are formatted, and a code indicating 16 worst case channels is then driven out to the I/O gear. This code will be used by the frequency domain analyzer to select the worst case channels for frequency analysis. It could also be used to drive a display of worst case channels and their limits. Assuming 51.6 msec of CPU time is used every 64 msec, CPU utilization would be 80 percent. This would leave 20 percent of CPU time to display worst case channels versus limits on a Tektronix or Grinnell display terminal. Over a 1-sec time period 200 msec of CPU time would be

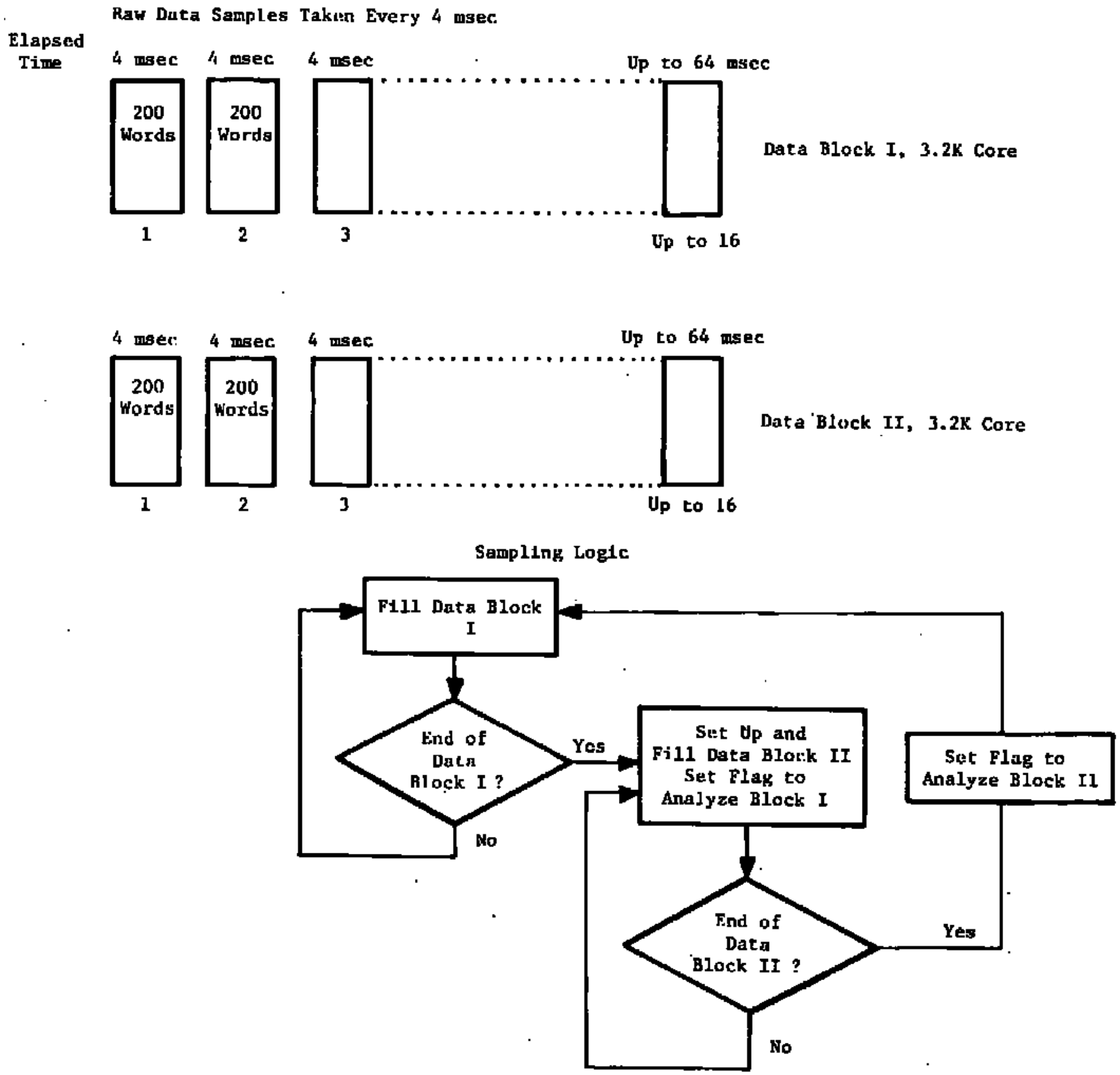
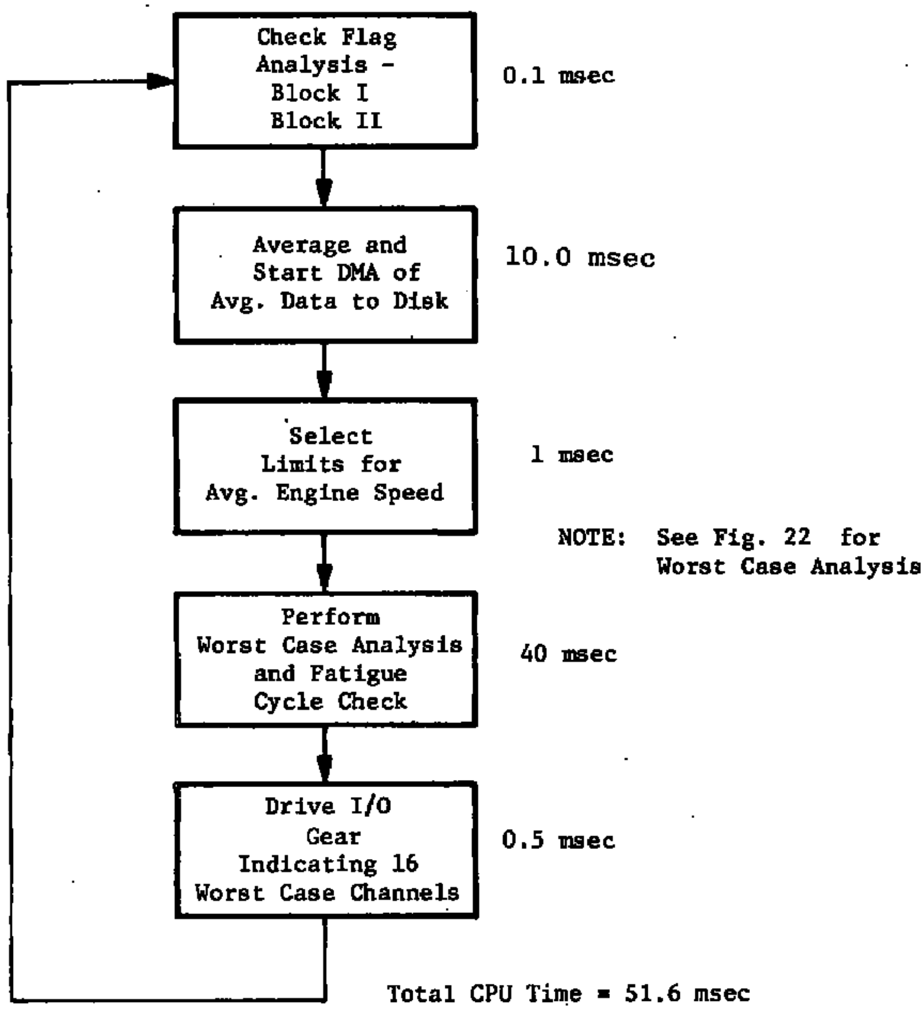
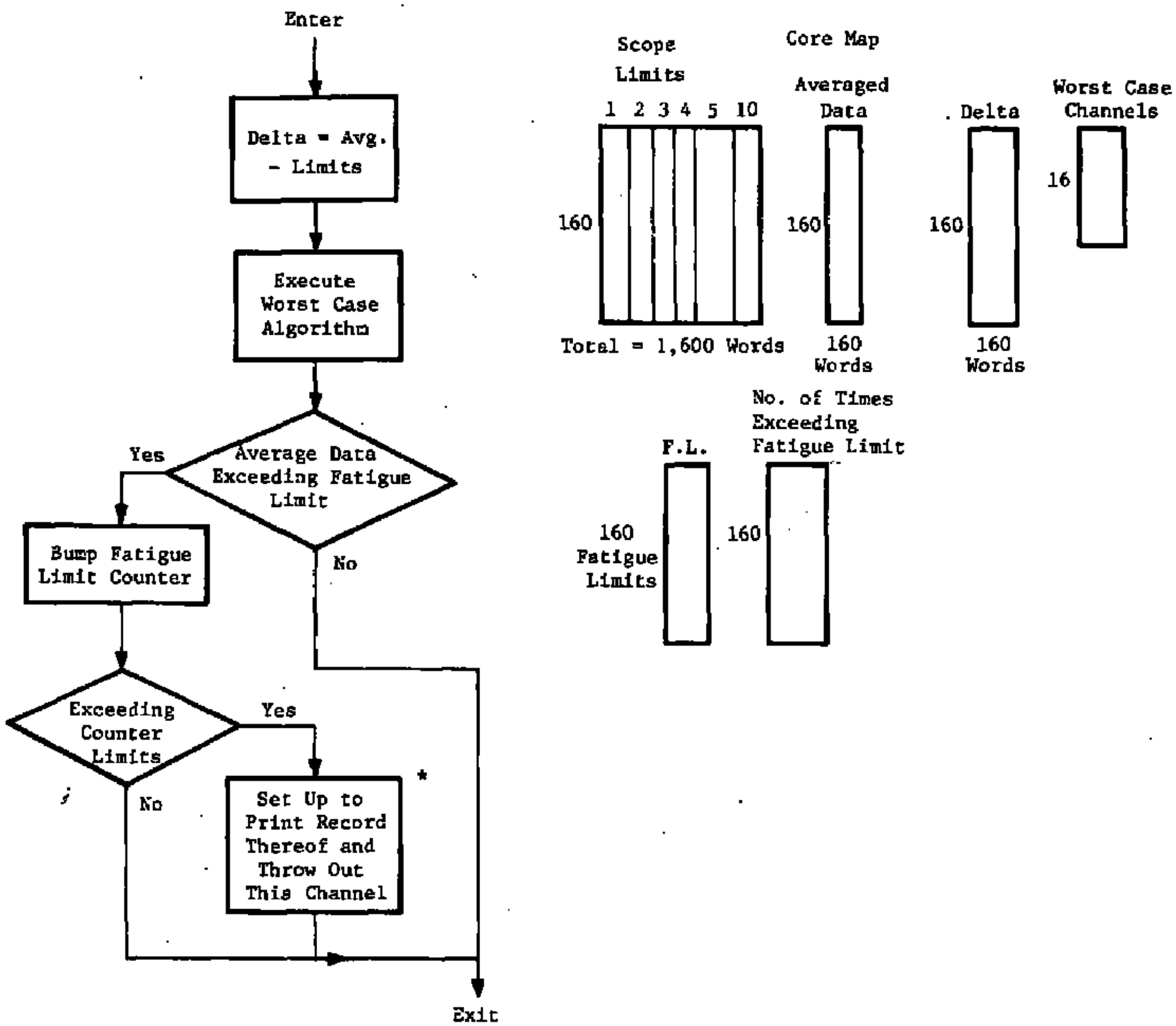


Figure 20. Sampling format and core map for proposed time domain system I.



If each scan occupies 4 msec, then one must produce a 16-sample average. If the scan rate is 10 msec, then an 8-sample average could be taken. If the scan rate is 15 msec, then a 4-sample average could be taken. See Fig. 20.

Figure 21. Flow chart for proposed time domain analysis I.



*Record printing would be a part of the display software and would occur in a time available mode. Typical delay times should be less than 10 sec.

Figure 22. Time domain system I worst case analysis and fatigue limit check.

available. Calculations for updating a screen will require at least 500 msec of CPU time. This means that the screen could be updated every 2 to 3 sec, allowing for DMA transfers and other miscellaneous overhead.

4.1.3 Summary of Specifications Satisfied by Time Domain System I

Time Domain System I satisfies the following specifications:

1. Group I and Group IV peak-to-peak Input Requirements (Sections 3.2.1 and 3.2.4).

2. Time Domain Analysis (Section 3.4.2).

3. Instant Data Replay (Section 3.4.4).

4. Calibration of all Inputs (Section 3.3). (The software was not detailed, because this function is not an online, real-time requirement. The system would perform this function prior to performing system analysis as stated in Section 3.4).

4.2 FREQUENCY DOMAIN SYSTEM I

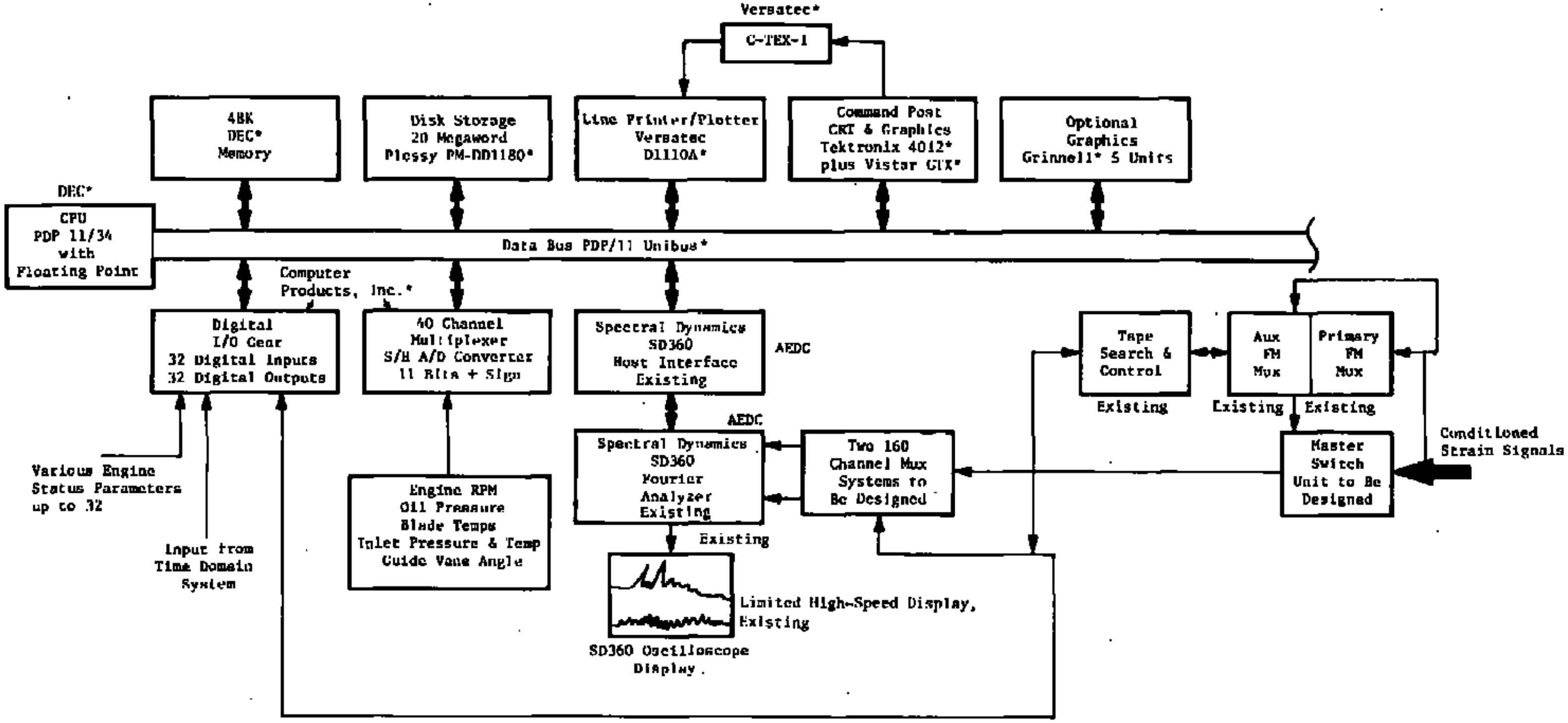
The proposed system is shown in Fig. 23 and is similar to the Time Domain System with the addition of a Fourier analyzer and two 160-channel MUX systems. The 200-channel multiplexer used in the Time Domain System I design is reduced to 40-channel capability, but identical equipment is specified for spare part capability. This holds true for all other equipment shown in Fig. 23.

4.2.1 Data Acquisition and System Software

This system would accept the 16 worst case channel number codes produced by the Time Domain System for further analysis. These 16 channels would be selected by the two 160-channel MUX systems on a pair basis. As Fig. 24 shows, two channels would be sampled, the Fourier transform of each channel would be taken, and transform results would be transferred to the 20-megaword disk pack on a DMA basis. Worst case analysis would take place using a five point limit scheme. The worst case algorithmn would involve:

1. Calculation of delta = C_n - C_n limit

2. Determination of worst case channel (i.e., the channel with the greatest delta on any one spectral line)



*Or equivalent hardware and software compatible with the chosen CPU.

Figure 23. Proposed frequency domain system I.

It is assumed that limits specified in Section 3.4 have been input and stored in the computer memory (the five point limit scheme with linear interpolation between points can be utilized to meet minimum requirements). As indicated in Fig. 24, the time required to sample all 16 channels and produce a Fourier transform (0 to 30 kHz) is approximately 0.5 sec. This time is determined by the Spectral Dynamics SD360 Fourier analyzer. The analysis uses ping-pong buffers for data storage and worst case analysis as previously described for the Time Domain System 1. It is estimated that worst case analysis could occur within 0.5 sec, which means that it would be possible to check all sixteen channels every 0.5 sec. Section 3.4.3 specified a check on all channels every 2.0 sec. It would be possible to update a slower-speed Tektronix or Grinnell system every 1 to 2 sec. Therefore, a designer must trade off display capability versus continuous monitoring capability every 0.5 sec. A good trade-off would be to update the screen every 5 sec in a background mode while continuously monitoring the 16 worst case channels every 1.00 sec. This would allow ample CPU time to update the screen with a worst case channel or plot a three-dimensional Campbell diagram as shown in Fig. 17. Spectrums would be produced at 5-sec intervals. This would be feasible since engine RPM speed changes are usually slow except during a throttle snap.

Display software will not be detailed because various companies such as Tektronix, Spectral Dynamics, General Radio, Grinnell, and Versatec have extensive plotting packages in the form of various subroutines. This software has been developed over the past 5 to 6 years and is constantly being refined. All of this software is available and will run in DEC PDP 11 computers. Efficient and economical display of data demands use of this software, which has been thoroughly documented by the various manufacturers.

4.2.2 Summary of Specifications Satisfied by Frequency Domain System I

Frequency Domain System I satisfies the following specifications:

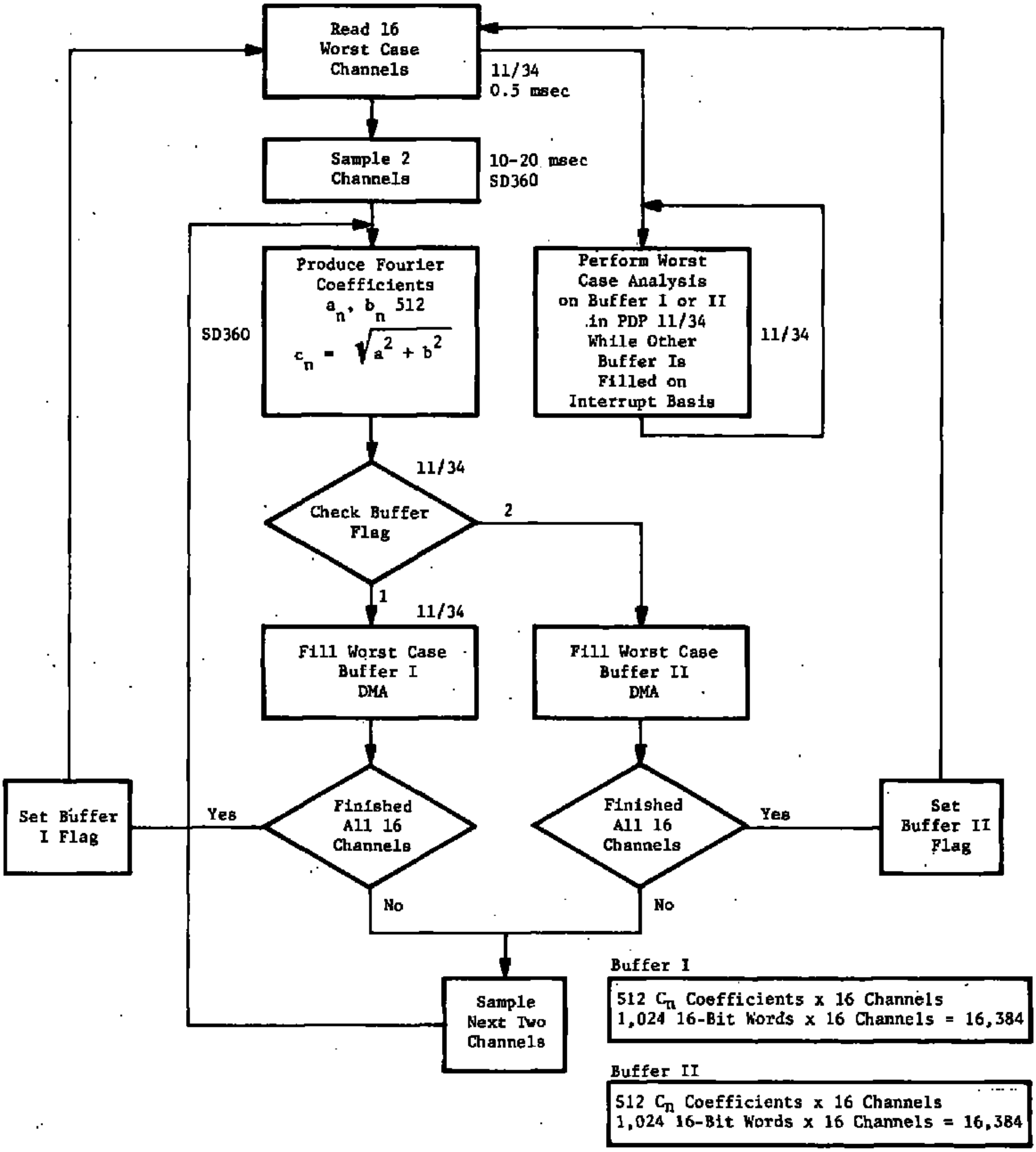
1. Group I and IV Strain-Gage Input Requirements (Section 3.2.1 and 3.2.4).

2. Frequency Domain Analysis (Section 3.4.3).

3. Instant Data Replay (Section 3.4.4).

4. Future Systems Analysis Capability (Section 3.5); The offline Analysis requirement is met by the SD-360 analyzer).

5. Calibration of all inputs (Section 3.3). (The software was not detailed because this function is not an online, real-time requirement. The system would perform this function prior to system analysis as stated in Section 3.4).



Total time required to sample all 16 channels, calculate C_n and Θ_n (512), and DMA all data to disk and 11/34/core would be approximately 0.5 sec. Worst case analysis would occur during the 0.5 sec required to fill the other buffer. Worst case analysis should not exceed 0.5 sec. Total core would be 48K.

Figure 24. Flow chart for frequency domain analysis I.

4.3 TIME DOMAIN SYSTEM II

The proposed system is identical to Time Domain System I except for the 200-channel multiplexer, dual port memory, and 160-channel fatigue limit counter. All but 40 channels of the 200-channel MUX have been replaced by a 160/16 selector, high-speed A/D conversion and control, an array processor unit and associated host interface, input/output processor (IOP), high-speed memory, and digital/analog output. Fig. 25 details this system.

There are two pieces of optional equipment:

1. Dual port memory

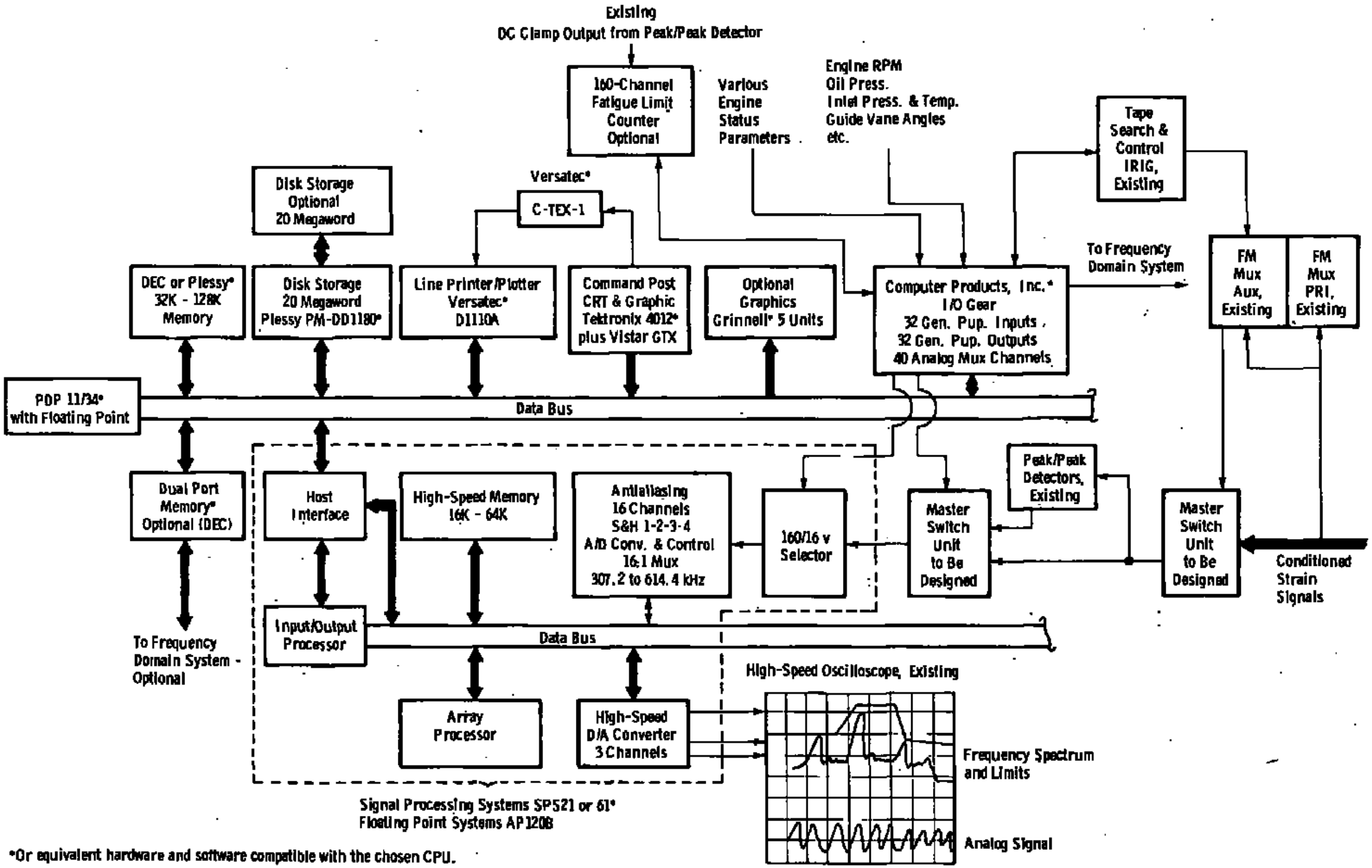
2. Fatigue limit counters

The dual port memory will provide higher speed communication to the frequency domain system and allow for direct communication. This means that future communication requirements, unforeseen at this time, could be easily met.

A conceptual design for a fatigue limit counter is indicated in Fig. 26. This counter would provide better limit cycle recordkeeping than System I. It would also free CPU time for additional analysis and recordkeeping in real time.

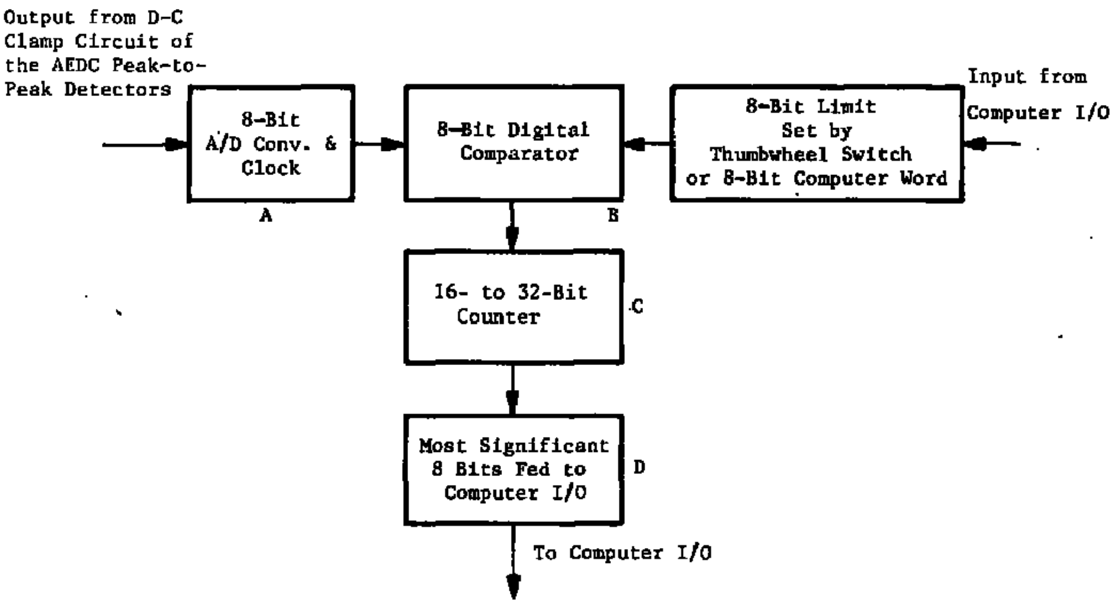
4.3.1 Data Acquisition

The multiplexer portion of this system will allow for simultaneous sampling of 2 to 16 channels. System I could look at only two channels at a time. The basic design approach was to provide a 160/16 premultiplexer (slow speed). The output of this MUX (16 outputs) is fed to 16 antialiasing filters (Rockland 816 computer controlled). These 16 channels are then high-speed multiplexed as shown in Fig. 27. This allows sampling of all 16 channels simultaneously, in groups of four, or one at a time. In groups of four, the basic spectrum band would be 300 kHz/8 = 37.5 kHz, which is more than adequate. However, the SD360 which was used in the System I design is capable of sampling two channels simultaneously at a rate of 307.2 kHz each. Duplicating this specification would require a 614.4 kHz A/D. Providing a 614.4 kHz A/D with this multiplexing scheme will allow for all foreseeable analysis requirements.



*Or equivalent hardware and software compatible with the chosen CPU.

Figure 25. Time or frequency domain system II.



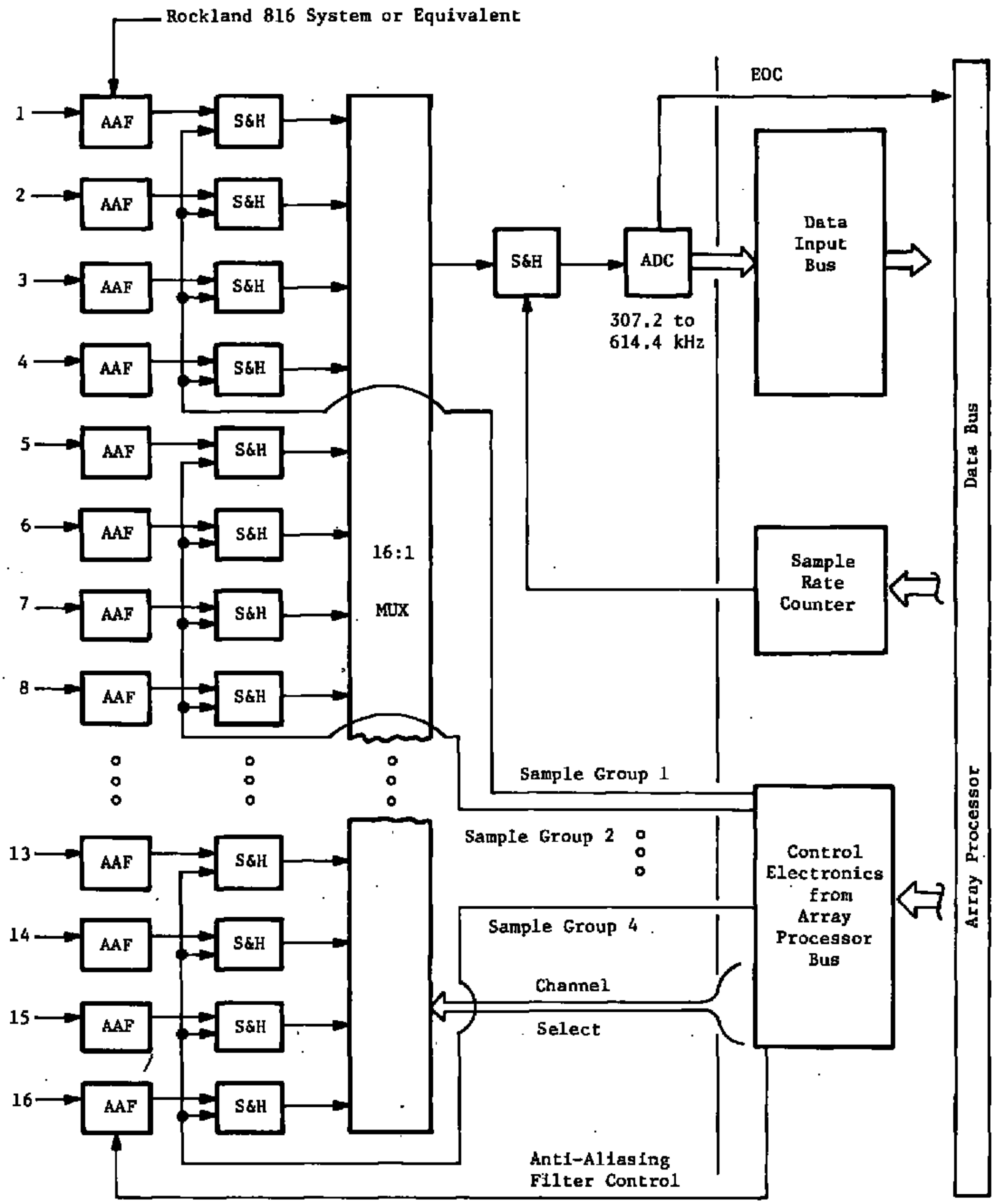
A. A/D converts signal to a digital word at a 60-kHz rate.

B. Comparator checks A/D word for above limit.

C. Counter counts the number of times the signal has exceeded limit.

D. The most significant 8 bits are fed to the computer I/O for record-keeping purposes.

Figure 26. Fatigue limit counter.



AAF = Antialiasing Filter

S&H = Sample and Hold

Figure 27. Sixteen-channel random input system.

4.3.2 Time Domain System II Advantages

Advantages of the Time Domain System II are as follows:

1. Increased throughput in averaging and storing peak-to-peak values (approximate factor of 10). The array processor would handle this function in lieu of the DEC 11/34 processor.

2. Ability to record peak-to-peak information as well as improved fatigue limit cycle information. (Note the 160-channel fatigue limit counters.) This also frees more 11/34 CPU time.

3. Ability to analyze the conditioned strain-gage signals, as well as peak-to-peak values, itself.

4. Improvement of online, real time graphics capability because online automatic analysis can take place in the array processor portion and display/housekeeping tasks can occur solely in the DEC 11/34 processor.

5. Option of using this system in frequency analysis as well as time domain analysis mode. A combination of frequency and time domain analysis is possible due to array processor computing power.

6. Ability to produce an online, real-time plot of overall peak-to-peak stress versus engine speed while performing automatic analysis as described for System I. The peak-to-peak stress plots would appear on the Tektronix and Grinnell graphic systems. The plots would be similar to Fig. 18. It is estimated that up to 16 different channels could be plotted simultaneously. Hard copy (from plotter) would then be obtained within 5 to 10 sec after the completion of an engine acceleration or deceleration. This satisfies Section 3.5, Future Analysis Requirements (Part 1).

4.4 FREQUENCY DOMAIN SYSTEM II, TWIN SYSTEM CONCEPT

This system would be essentially a twin to the Time Domain System II and would be configured as shown in Fig. 25. The two systems would have identical hardware. The software in each system would run in a parallel, asynchronous mode.

Advantages of the Frequency Domain System II are as follows:

1. Increased flexibility with respect to frequency analysis, increased throughput speed, and a more flexible high-speed display system.

2. Ability of twin systems to do frequency analysis in parallel. This would effectively double frequency domain capability.

3. High-speed data inputs on both systems from optical inputs or PCM data inputs as will be described for a System III.

4. Ability to meet all of the maximum requirements as stated in Section 3.5 through extensive online, real time plotting of frequency data.

5. Excellent throughput for offline analysis. Automatic production of report data packages could be produced overnight by using both systems in parallel. This means that if an engine test ended at 6 p.m., a complete report package (Campbell diagrams, etc.) would be ready by 7 a.m. the next morning or perhaps even sooner.

4.5 TIME AND FREQUENCY DOMAIN SYSTEM III

This system is produced by adding optical input gear which satisfies Section 3.2.3 Group III input requriements and pulse code-modulated (PCM) data input equipment which satisfies Section 3.2.2 Group II input requirements. Figure 28 details the addition of this capability and a 20- to 40-megaword high-speed disk pack to be used for storage of high-speed optical data and selected PCM-generated data.

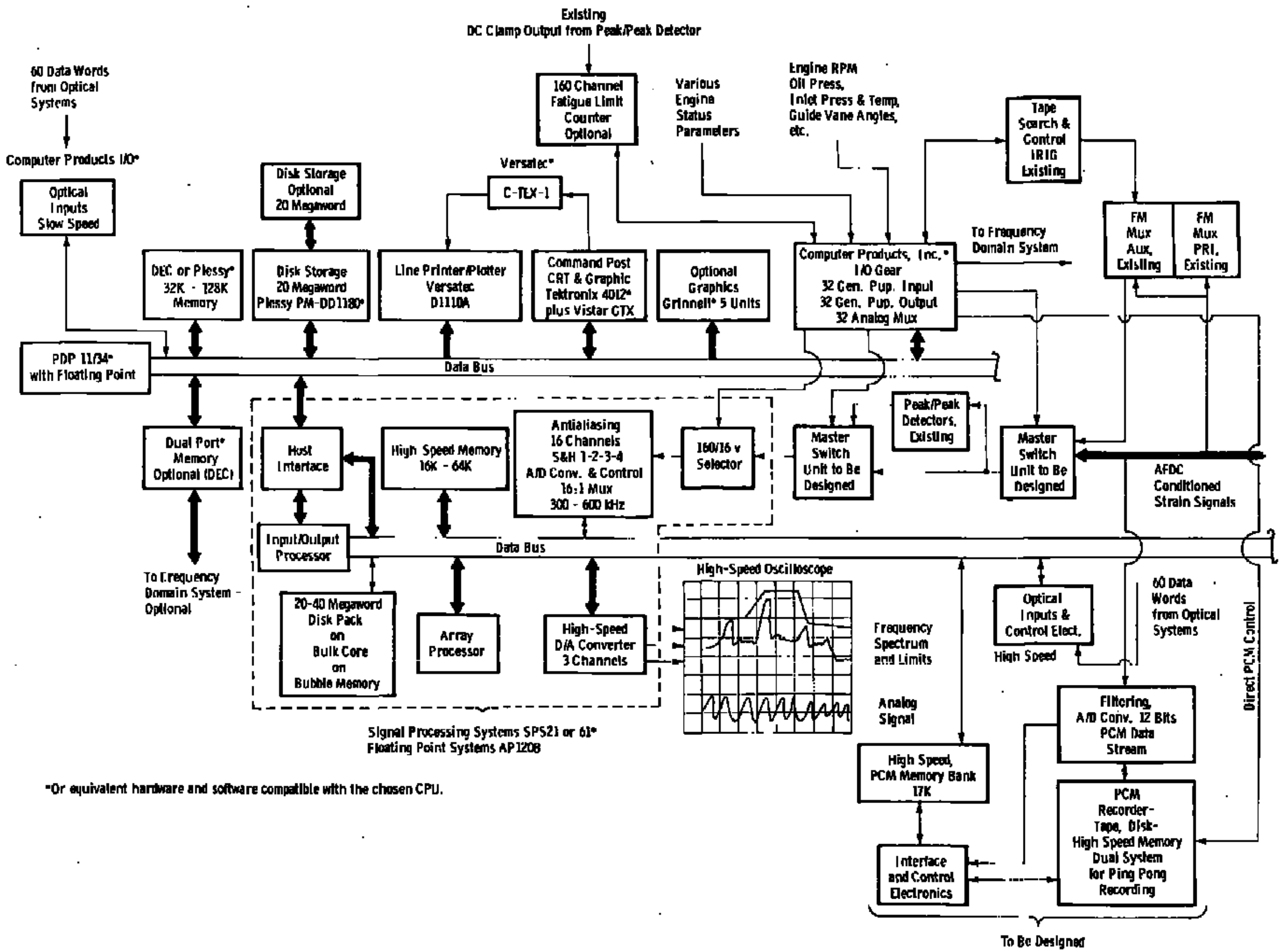
4.5.1 Optical Inputs

There are two types of gear indicated: slow-speed, low cost, and high-speed, high cost optical gear. The slow-speed gear is standard off-the-shelf hardware input from Computer Products Company capable of accepting 60 words (16 bit). This information could be read on a DMA or interrupt basis into the DEC 11 memory or directly to the disk pack. The high-speed optical gear would be a custom-designed product. It would interface to the array processor bus and its input/output control electronics. The high-speed gear would have distinct advantages such as the following:

1. Display capability would be enhanced both for high-speed and slow-speed display modes.

2. Using twin system concepts, the Time Domain System would have more than adequate time to handle peak-to-peak data, optical data, and possibly strain data, all on a parallel basis.

3. Optical data as well as the results of peak-to-peak analysis could be displayed simultaneously on the Tektronix and Grinnell systems.



*Or equivalent hardware and software compatible with the chosen CPU.

Figure 28. Time or frequency domain system III.

4.5.2 PCM Data System

Preliminary concepts of a PCM system include the following:

1. Filtering of each channel to eliminate aliasing of data.

2. A/D conversion of each channel at a 60-kHz conversion rate (minimum) with 11 bits + sign.

3. Parallel piping of A/D conversion results to two sources. The first source would be the PCM recording medium. The second source would be a PCM Control Electronics interface which had been fed all 160 digitized channels in parallel. This interface would place in memory on a sequential basis the results of each conversion on each channel. This would require up to 160 words for each conversion, assuming a 160-channel system. With synchronous conversion on each channel, 160 words would be produced every 1/60 kHz = 16.67 μsec. One hundred scans would require 16K words and would take place in 1.67 msec. The control electronics would then proceed to overlay the first scan and repeat this process continuously. An extra 1K of memory would be used for control of the PCM recorder and for selecting various scan combinations if all 160 channels were not to be continuously scanned.

This scheme allows reading of digitized data much the same as the analog input system; it alleviates the need for online, real time array processor overhead and essentially emulates the capability of the analog input system. Instant replay and other analysis modes would be handled in the same manner through I/O gear control path or the control memory and electronics section.

It is suggested that such a system be designed and proposed by the various vendors who have extensive experience in this field. Such a design, using the concepts presented, should be developed within the next two years; if it proved feasible, hardware could be supplied within the next three to five years, depending on technical and fiscal resource limitations.

4.5.3 High-Speed Data Storage

In addition to the PCM system and optical gear, a high-speed interface to a high-speed 20- to 40-megaword disk, bulk core, or bubble memory is proposed. This interface would offer transfer rates in excess of 1 MHz (16 bits, 1 μsec/word) and near-zero seek times. It would be interfaced to the high-speed data bus on a DMA basis, minimizing IOP and array processor overhead. This would be a future design, and it is expected that technology will provide a cost effective product within the next five years.

4.6 SOFTWARE CONSIDERATIONS: SYSTEMS I, II, and III

A software systems design must be developed using the "structured" or so called "top down" approach. Fig. 29 shows a conceptual diagram for such a design.

The overall job must first be stated and then broken into various functional tasks. This can take place before hardware has been considered. Sections 2.0 and 3.0 provide information that must be used to accomplish this task. Every effort must be made to break each large task into smaller and smaller tasks that eventually become equipment-peculiar hardware drivers (PHD). Each PHD can then be written for a piece of gear. If hardware is changed, one need only change the driver or add a new driver to accomplish a new overall task. Software blocks already written can then be interspersed within any given master subroutine caller. If the blocks do not exist, they can then be added, just as all other blocks were in the beginning. This type of programming demands a uniform calling and communication mode for all software modules. The computer industry is moving in this direction, and many subroutines at the PHD level have already been written and checked. Efficient use of programming manpower demands heavy use of this software. Because all system hardware has been designed on a modular basis, effective use of such hardware requires modular software. The three-level system that has been designed lends itself to such a programming philosophy.

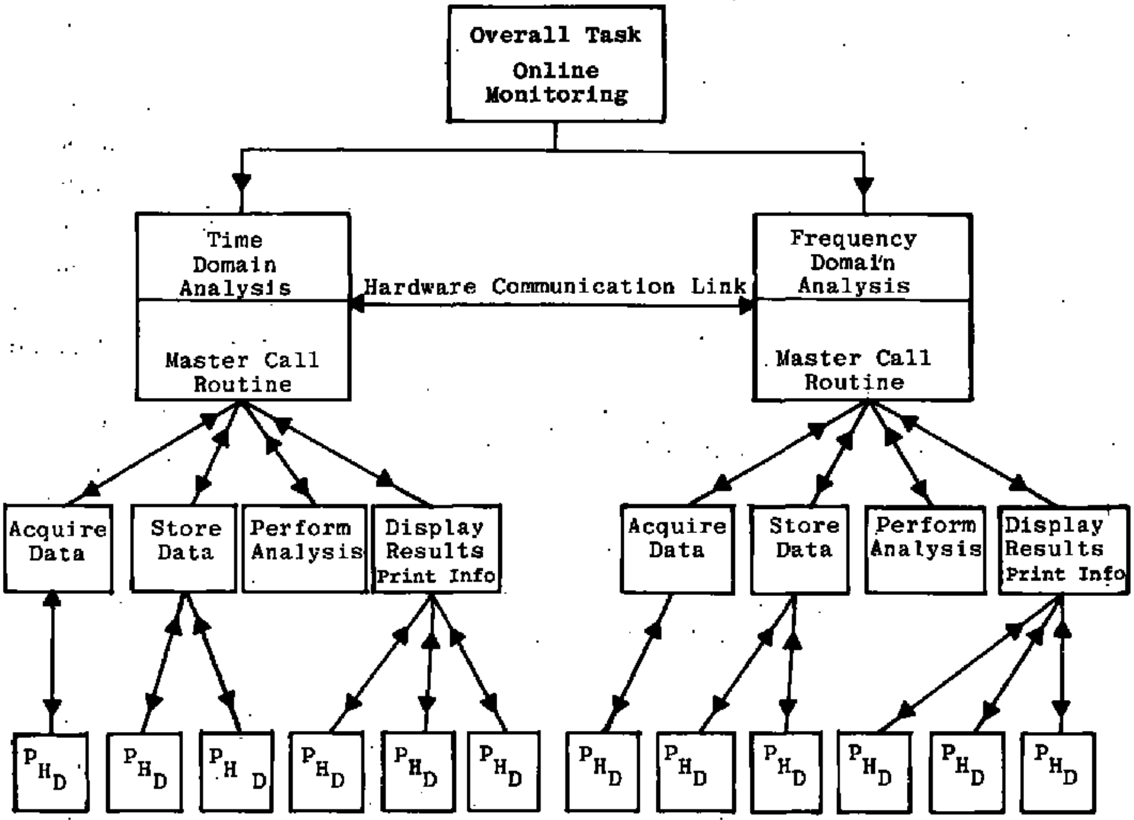
4.7 PORTABILITY CONCEPTS

The research involved in this report led to many conversations with various research organizations, other divisions at AEDC, and various manufacturers of jet engines. A concept was developed for providing portability of this equipment. There are two approaches for such a capability.

1. Rack mounting of all equipment on forklift skids or dollies so that equipment can be set up at a given location in semipermanent fashion. Connections to all equipment from the engine and facility would be through a one-rack interface point containing barrier terminal strips or connectors.

2. Mounting of all equipment in a large van or bus.

An umbilical cord, connector, or barrier terminal strip concept would be utilized for input of data to the system. An alternate power source (isolated) could be provided by an onboard gasoline or diesel-driven generator. The umbilical cord for data signals would be calibrated for strain-gage channels with respect to frequency characteristics.



Peculiar Hardware Driver (PHD)

Each peculiar hardware driver could consist of several sublevels of call hierarchy.

Figure 29. Structuring of software.

Making such a system mobile would not limit its use to any one test cell or group of cells. Moreover, this system could be used for any type of dynamic data analysis as well as stress analysis. This would allow efficient and effective use of manpower as such a system could be staffed by a small group such as an equipment technician and two combination analysis/software/hardware system engineers. Basic setup and equipment operation would be handled by the technician on a procedural basis. The two system engineers would provide an intelligent user interface and would translate test requirements for maximum and efficient system use.

4.8 SYSTEM DESIGN SUMMARY

The three systems have been designed on an "upward compatible," modular basis. The starting point for system evolution will be determined by relative system costs, availability of funds, and the time periods required to produce a working system. The system design as presented utilizes system cost, ease of implementation, and system requirements as equal factors in making cost/capability trade-off decisons.

5.0 SUMMARY AND CONCLUSIONS

The improvement philosophy stated in the Introduction was employed to produce a set of specifications from which an improved system could be designed. The information presented in Section 2.0 in conjunction with the References proved to be a valuable aid with respect to the statement of requirements and system design.

The requirements statement produced a three-level system design. System I satisfies present minimum improvement requirements. System II, which can be evolved from System I due to modularity, flexibility, and expansion requirements, will satisfy present maximum requirements. System III can be created from System II simply by adding hardware inputs and software for processing future optical and PCM data.

A System II or III capability could offer pre- and posttest analysis (limited finite-element and modal analysis) in addition to online analysis as described. These systems could be interfaced to any large central computer capability and used as an intelligent preprocessor for in-depth finite element and modal analysis, which could include modeling of entire compressor and engine assemblies. In addition, System I, II, or III could be interfaced (hardware and software) to a controls system as described in Section 3.5, thus satisfying future automatic control requirements.

Detailed cost figures were not included in this report even though system cost, implementation, and system requirements were all considered equal factors in the system design. A detailed cost analysis and implementation schedule is being formulated for the optimum development and implementation of a system for the AEDC test facilities.

REFERENCES

1. Miller, F. E. and Doeringsfeld, H. A. Mechanics of Materials. International Textbook Company, Scranton, Pennsylvania, 1962 (Second Edition).

2. Bode, G. M. and Drier, D. W. "Gas Turbine Technology - Part I - Turbine Mechanical Design Procedures." NASA Lewis Research Center, Cleveland, Ohio, April 1975.

3. Armstrong, E. K. and Stevenson, R. E. "Some Practical Aspects of Compressor Blade Vibration." The Journal of the Royal Aeronautical Society, Vol. 64, No. 591, March 1960, pp. 117 to 130.

4. Armstrong, E. K. "Recent Blade Vibration Techniques." Transactions of the ASME, Vol. 89, No. 3, July 1967, pp. 437 and 444.

5. Hartog, J. P. Den. Mechanical Vibrations. McGraw-Hill Book Company, New York, 1956 (Fourth Edition).

6. Lathi, B. P. Communications Systems. John Wiley & Sons, Inc., New York, 1968.

7. Fowler, R. B. and Habernicht, G. W. "Frequency Analysis by the Computer Evaulation of the Fast Fourier Transform." Undergraduate Thesis, Christian Brothers College, Memphis, Tennessee, June 1969.

8. Harris, F. J. "Trigonometric Transforms." Technical Publication No. DSP-005 6/76, Spectral Dynamic Corporation, San Diego, California, June 1976.

9. Bendat, J. S. and Piersol, Allan E. Measurement and Analysis of Random Data. John Wiley and Sons, New York, 1966.

10. Chamis, C. C. "Vibration Characteristics of Composite Fan Blades and Comparison With Measured Data." NASA TMX-71893, NASA Lewis Research Center, Cleveland, Ohio, May 1976.

11. Schaeffer, H. G. "Nastran Primer." University of Maryland, Aerospace Engineering, College Park, Maryland, Skidmore Printing Service, 1977.

12. Danforth, E. E. "Blade Vibration: Some Key Elements in Design Verification." General Electric Company, Cincinnati, Ohio, 1977.

13. Nieberding, W. C. Pollack, J. L. "Optical Detection of Blade Flutter." NASA TMX-73573, Lewis Research Center, Cleveland, Ohio, March 1977.

NOMENCLATURE

A/D	Analog to digital
a_n	Fourier Series coefficient
b_n	Fourier Series coefficient
CPU	Central processing unit
c_n	Fourier Series coefficient
DEC	Digital Equipment Corporation
DMA	Direct memory access
D/A	Digital to analog
db	decibel
E	Energy density
EO	Engine ordered
FFT	Fast Fourier Transform
FM	Frequency multiplexed
F(t)	Function of time
F(w)	Function of frequency
Hz	Frequency in hertz (cycles per second)
I/O	Input-output
IOP	Input-output processor
IRIG	Inter-range Instrumentation Group Standard Time Code
K,k	One thousand
°K	Temperature in degrees Kelvin
kHz	Frequency in kilohertz

kpsi	Kilopounds per square inch
kRPM	One thousand revolutions per minute
LC	Limit cycle instability or flutter
LSB	Least significant bit
lim	Limit
MHD	Magnetohydrodynamics
MHz	Frequency in megahertz
MUX	Multiplex
msec	Milliseconds
mv	Millivolt
N	Number of stress cycles
n_a	Safety factor, fatigue limit
n_m	Safety factor, yield point
P	Power in watts
PCM	Pulse code modulation
PHD	Peculiar hardware driver
pk-pk	Peak-to-peak
R	Resistance
RMS	Root mean square
RPM	Revolutions per minute
rev	Revolution
SAP	Structural analysis program
SFV	Separated flow vibration

$S_f(w)$	Power density spectrum
T	Time period used for Fourier analysis
t	Time in seconds (subscript g refers to any given time)
V	Volt
VDC	Volts direct current
1E	First edgewise fibration mode
1F	First flexural vibration mode
2F	Second flexural vibration mode
1T	First torsional vibration mode
ϵ	Strain
θ	Angle in degrees
μsec	Microseconds
π	3.14159
Σ	Summation of all terms
σ	Stress in pounds per square inch
ω	Frequency in radians per second